Chapter 4
Competitiveness

4.1   PERFORMANCE DEMONSTRATION RESULTS

4.1.1   Background

This section of the Cleaner Technologies Substitutes Assessment (CTSA) summarizes the performance testing of the surface finishing technologies. To conduct the performance evaluation, a test board was designed and fabricated, then 16 different surface finishes were applied at 13 volunteer printed wiring board (PWB) manufacturing sites, in the U.S. and England, during "performance demonstrations" between May and July, 1998. The performance of the alternative surface finishes, taken in conjunction with risk, cost, and other information in this document, provides a more comprehensive assessment of alternative technologies.

In a joint and collaborative effort, Design for the Environment (DfE) project partners organized and conducted the performance demonstrations. The demonstrations were open to any supplier of surface finishing technologies who chose to submit product line information and nominate appropriate demonstration sites. Prior to the start of the demonstrations, DfE project partners advertised the project and requested participation from all interested suppliers through trade shows, conferences, and direct telephone calls.

A summary of the methodologies used and key results are presented in this chapter. Additional results, details on testing and analysis methodologies, and more information on the test board design, can be found in Appendix F.

The assembled PWBs used in the performance demonstration provided electrical responses for 23 individual circuits that fall into seven major circuit groups. The first four circuit groups had both plated through hole (PTH) and surface mount technology (SMT) components.

- high current low voltage (HCLV),
- high voltage low current (HVLC),
- high speed digital (HSD),
- high frequency low pass filter (HF LPF),
- high frequency transmission line coupler (HF TLC),
- leakage networks, and
- stranded wire (SW).

The design of the assembled PWB made it an excellent discriminating test vehicle to discover problem areas associated with new technologies, materials, and processes. Test boards were exposed to the following test conditions ("environmental testing") to accelerate the discovery process:

- 85/85: 85°C and 85% relative humidity for three weeks),
- thermal shock (TS): 200 cycles between -50°C and 125°C, and
- mechanical shock (MS): dropped 25 times from a height of three meters onto a concrete surface)

In general, each of the surface finishes applied during the performance demonstrations were very robust under the conditions of the three tests. Some problem areas did develop, however, during the testing. In particular, a problem area with HF LPF circuits related to open PTHs was identified. The number of HF LPF anomalies was compared to the amount that would be expected under a hypothesis that anomalies are independent of surface finish. This analysis led to the following summary statements about the HF LPF circuits with respect to each surface finish:

- Hot air solder leveling (HASL) anomalies were close to the expected values throughout the three tests.
- Nickel/gold had far fewer anomalies than expected for all circuits.
- Nickel/palladium/gold had far fewer anomalies than expected for all circuits.
- Organic solderability preservative (OSP) anomalies were close to expected values, except for one HF LPF SMT circuit where there were more anomalies than expected.
- Immersion silver had many more anomalies than expected for all circuits.
- Immersion tin anomalies were close to expected for PTH circuits, but were higher than expected for SMT circuits.

The number of open PTH anomalies in the HF LPF circuit may have been related to the inherent strength of the metals, as well as to board design (i.e., the small diameter vias in this circuit). Product designers should be aware of these phenomena when considering a change of surface finishes.

Other notable anomalies were in the HCLV SMT and HVLC SMT circuits in the mechanical test, during which SMT components across all surface finishes fell off the board.

A failure analysis was conducted on the test boards that failed the 85/85 test and on a control group not subjected to the test, in order to determine if any links existed between board contamination from fabrication and assembly process residues and the electrical anomalies. In addition, the boards were inspected visually to identify any obvious anomalies or defects. The results indicated that the failures were not a result of residue, and that solder cracking was the most common visual defect. HASL had more solder cracks than the other finishes.

4.1.2 Performance Demonstration Methodology

The general plan for the performance demonstration was to collect data on alternative surface finishing processes, during actual production runs, at sites where the processes were already in use. These demonstration sites were production facilities, customer testing facilities (beta sites), or supplier testing facilities. Whenever possible, production facilities were used. Each demonstration site received standardized test boards, which were run through the surface

finishing operation during their normal production. The information collected through the demonstrations was intended to provide a "snapshot" of the way the technology was performing at that particular site at that particular time. This methodology was developed by consensus with the technical workgroup, which included suppliers, trade association representatives, EPA, and PWB manufacturers. A detailed performance demonstration methodology is included in Appendix F.

Each supplier was asked to submit the names of up to two facilities at which the demonstrations of their technology were to be conducted. This selection process encouraged the suppliers to nominate the facilities where the technology was performing at its best. This, in turn, provided for more consistent comparisons across technologies. The demonstration sites included 13 facilities, at which 16 different demonstrations were run.

To minimize differences in performance due to processes other than surface finishing, the panels used for testing were all manufactured at one facility, Network Circuits, in Irving, Texas. After fabrication, the panels were numerically coded for tracking purposes, and six panels (containing four boards per panel) were shipped to each demonstration site, where the appropriate surface finish was applied.

An observer from the DfE project team was present at each demonstration site to monitor the processing of the test panels. Observers were present to confirm that the processing was completed according to the methodology and to record data. Surface finish application at each demonstration site was completed within one day, while performance processing at all sites was completed over a three-month period.

When the processing was completed, the panels were put into sealed bags and shipped to a single facility, which acted as a collection point for all performance demonstration panels. Completed panels were then shipped back to Network Circuits, where the panels were cut into boards. All coded boards were then shipped to a single facility (EMPF/American Competitiveness Institute) for assembly. One subgroup was assembled using low-residue (LR) flux and the other with water soluble (WS) flux.

Following assembly, the boards were sent to Raytheon Systems Inc. in McKinney, Texas, where the performance characteristics of the assembled boards were tested. Testing included Circuit Electrical Performance and Circuit Reliability testing. The Electrical Performance testing assessed the circuit performance of the printed wiring assemblies (PWAs), or assembled PWBs, before and after exposure to $85\,^\circ$C temperatures at 85% relative humidity for 3 weeks. For the Circuit Reliability testing, the same PWAs were tested after being subject to thermal shock and mechanical shock conditions.

Limitations of the Performance Demonstration Methodology

The performance demonstration was designed to provide a snapshot of the performance of different surface finishing technologies. Because the demonstration sites were not chosen randomly, the sample may not be representative of all PWB manufacturing facilities in the U.S. (However, there is no specific reason to believe that they are not representative.)

4.1.3   Test Vehicle Design

The test vehicle design was based on a test board designed by the Sandia National Laboratory Low-Residue Soldering Task Force (LRSTF). This test vehicle was used by the Circuit Card Assembly and Materials Task Force (CCAMTF), a joint industry and military program evaluating several alternative surface finishing technologies. The design is a functional PWA designed to test *process effects* resulting from changing materials and processes, and to mitigate as much risk as possible in process change. The PWA and the test/data analysis methodology are considered excellent discriminators in comparing processes fluxes, surface finishes, or other process technologies. It should be noted that circuit technology continues to change rapidly; the PWA design is based on 1994 technology and does not incorporate some more recent, state-of-the-art, circuitry. It is unknown whether the results might have differed with newer circuit technology. However, the test PWA was designed to contain approximately 80 percent of the circuitry used in military and commercial electronics. In addition, use of this test vehicle by the DfE PWB Project provided great savings in cost and time that would be required to develop a new test vehicle, and allows for some comparison with CCAMTF results.

The test vehicle was designed to be representative of a variety of extreme circuits: high voltage, high current, HSD, low-leakage current, and high frequency (HF) circuits. A designer can use the resulting measurements to make some analytical judgments about the *process* being tested. The test PWA was not intended to be a "production" board, which would typically be too narrow in breadth to represent a wide variety of these circuit extremes. Even though some technology complexities/advancements are not duplicated, the basic types are represented, and comparison of baseline technologies can be extrapolated, in some cases, to more current technology by analysis. The performance results are assessed based on the acceptance criteria developed by the CCAMTF project, which are described in Table 4-1.

The test PWA measures 6.05" x 5.8" x 0.062". See Appendix F for more details on the design of the test PWA. The PWA is divided into six sections, each containing one of the following types of electronic circuits:

- HCLV;
- HVLC;
- HSD,
- HF;
- SW; and
- other networks.

The components in the HCLV, HVLC, HSD, and HF circuits represent two principal types of soldering technology:

- PTH: Leaded components are soldered through vias in the circuit board by means of a wave soldering operation.
- SMT: Leadless components are soldered to pads on the circuit board by passing the circuit board through a reflow oven

The other networks used for current leakage measurements are 10-mil pads, a socket for a pin grid array (PGA), and a gull wing. The two stranded wires (SW) are hand soldered.

The test vehicle provides 23 separate electrical responses as shown in Table 4-1. The criteria for 17 of the 23 circuits require a comparison to the pre-test measurements (i.e., before exposure to test environments), while the criteria for the remaining six circuits are based on absolute responses. The CCAMTF project conducted baseline testing for 480 test PWAs, which were used as the basis of the acceptance criteria that were published in their Joint Test Protocol. These criteria are also shown in Table 4-1.

It should be noted that these acceptance criteria are not absolutes, but rather guidelines based on engineering judgement and experience with the particular circuit. Therefore, in some cases when values that are just outside the acceptance criterion, they may be considered "not of practical significance." This would be the case when a single observation is close to the acceptance criterion. For example, if the criterion specifies an acceptable increase of 10dB and the increase for one board was measured at 10.2dB, it would be difficult to make any conclusion from a single observation so close to the acceptance criterion. However, if all HASL boards, for example, measured 10.2dB while all other surface finishes were below 10dB, it would be reasonably clear that there is an effect due to the surface finish.

The test PWAs were manufactured with the following six surface finishes for the DfE PWB Project:

- HASL;
- nickel/gold;
- nickel/palladium/gold;
- OSP;
- immersion silver; and
- immersion tin.

Additional information about each technology, including a process flow diagram and a description of each process step, is presented in Section 2.1, Chemistry of Use and Process Description.

Table 4-1. Electrical Responses for the Test PWA and Acceptance Criteria

Electrical Response	Circuitry	Acceptance Criteria
High Current Low Voltage		
1	HCLV PTH	Change in voltage from pre-test < 0.50V
2	HCLV SMT	Change in voltage from pre-test < 0.50V
High Voltage Low Current		
3	HVLC PTH	4µA < x < 6µA
4	HVLC SMT	4µA < x < 6µA
High Speed Digital		
5	HSD PTH Propagation Delay	< 20% increase from pre-test
6	HSD SMT Propagation Delay	< 20% increase from pre-test
High Frequency Low Pass Filter		
7	HF PTH 50MHz	Within ± 5dB of pre-test
8	HF PTH f (-3dB)	Within ± 50MHz of pre-test
9	HF PTH f (-40dB)	Within ± 50MHz of pre-test
10	HF SMT 50MHz	Within ± 5dB of pre-test
11	HF SMT f (-3dB)	Within ± 50MHz of pre-test
12	HF SMT f (-40dB)	Within ± 50MHz of pre-test
High Frequency Transmission Line Coupler		
13	HF TLC 500MHz Forward Response	Within + **[±?]** 5dB of pre-test
14	HF TLC 500MHz Forward Response	Within ± 5dB of pre-test
15	HF TLC 1GHz Forward Response	Within ± 5dB of pre-test
16	HF TLC Reverse Null Frequency	Within ± 50MHz of pre-test
17	HF TLC Reverse Null Response	< 10dB increase over pre-test
Other Networks: Leakage		
18	10-mil Pads	Resistance > 7.7 $\log_{10}$ ohms
19	PGA-A	Resistance > 7.7 $\log_{10}$ ohms
20	PGA-B	Resistance > 7.7 $\log_{10}$ ohms
21	Gull Wing	Resistance > 7.7 $\log_{10}$ ohms
Stranded Wire		
22	Stranded Wire 1	Change in voltage from pre-test< 0.356V
23	Stranded Wire 2	Change in voltage from pre-test < 0.356V

HCLV = high current low voltage; HF = high frequency; HSD = high speed digital; HVLC = high voltage low current; PGA = pin grid array; PTH = plated through hole; SMT = surface mount technology; TLC = transmission line coupler.

These surface finishes were applied at one or more of the different demonstration sites. Table 4-2 provides a summary of the 164 PWAs that were subjected to environmental testing by surface finish, manufacturing site, and flux type. Table 4-2 also shows that both fluxes were not used with all demonstration sites, and that 84 PWAs were processed with low residue flux, while 80 PWAs were processed with water soluble flux.

Table 4-2. Distribution of the Number of LRSTF PWAs by Surface Finish, Site, and Flux

Surface Finish	Site	Low Residue Flux	Water Soluble Flux
HASL	1	8	8
	2	8	—
	3	—	8
Nickel/Gold	13	4	8
	14	8	—
	15	—	8
Nickel/Palladium/Gold	16	8	4
OSP	4	4	—
	5	8	8
	6	8	8
Immersion Silver	11	8	4
	12	—	8
Immersion Tin	7	4	8
	8	8	—
	9	8	—
	10	—	8
Total No. of Boards:		84	80

Due to the uneven distribution of fluxes during assembly, the number of PWAs are different for each surface finish, as follows:

Surface Finish	No. of PWAs (Percent of total)
HASL	32 (19.5%)
Nickel/Gold	28 (17.1%)
Nickel/Palladium/Gold	12 (7.7%)
OSP	36 (22.0%)
Immersion Silver	20 (12.2%)
Immersion Tin	36 (22.0%)
Total	**164**

4.1.4   Environmental Testing Methodology

Each of the 164 PWAs summarized in Table 4-2 was exposed to the following environmental test sequence:

- Exposure to three weeks of 85°C and 85% relative humidity.
- 200 cycles of thermal shock with the PWAs rotated between chambers at -50°C and 125°C with 30 minute dwells at each temperature.
- Mechanical shock where the PWA is mounted in a rectangular fixture and dropped 25 times on a concrete surface from a height of 1 meter.

| 3 weeks of 85/85 | $\longrightarrow$ | Thermal Shock | $\longrightarrow$ | Mechanical Shock |

The PWAs were functionally tested prior to exposure to these environments and after each environment. Although the sequential nature of the tests may affect the results (i.e., the PWAs may be weakened in the mechanical test because of the previous two tests), the testing sequence was planned to minimize any carryover effect. The 85/85 environment was the first test because it is relatively benign with respect to impacts on the functionality of the PWA. In contrast, the mechanical shock test was performed last because it can cause separation of SMT components and therefore permanent damage to the PWA.

4.1.5   Analysis of the Test Results

General Linear Models

General linear models (GLMs) were used to analyze the test data for each of the 23 electrical circuits in Table 4-1 at each test time. The GLM analysis determines which experimental factors or combinations of factors (interactions) explain a statistically significant portion of the observed variation in the test results, and in quantifying their contribution.

Analysis of Variance and Multiple Comparisons of Means

Another statistical approach can be used to determine which groups of site/flux *means* are significantly different from one another for a given electrical response from the test PWA. This procedure begins with an analysis of variance (ANOVA) of the test results (Iman, 1994) for a given circuit. An ANOVA is perhaps best explained via an example.

An ANOVA performed on the 164 pre-test measurements for HCLV PTH produced the following:

Source	DF	Sum of Squares	Mean Square	F-Statistic	P-Value
Site/Flux	22	0.2908	0.0132	0.70	0.838
Error	141	2.6796	0.0190		
Total	163	2.9704			

The meaning of the terms in each of the columns of the ANOVA table is now given.

Source. The entries in this column represent the following:

- Site/Flux refers to the 23 site/flux combinations listed in Table 4-3.
- Error refers to the random/unexplained variation in the HCLV PTH voltage measurements.
- Total refers to the total variation in the data.

Degrees of Freedom. The numbers in this column represent a statistical term known as the degrees of freedom (DF). The degrees of freedom associated with each source are calculated as follows:

Site/Flux   23 - 1 (the number of site/flux combinations - 1) = 22
Error   Total DF - Site/Flux DF = (164 - 1) - (23 -1) = 163 - 22 = 141
Total   164 - 1 (the number of test measurements -1) = 163

Sum of Squares. The entries in this column are the sums of squares associated with each source of variation. The Total Sum of Squares is calculated by summing the squares of the deviations of the 164 data points from the sample mean. If this number were divided by 164 - 1, the result would be the usual sample variance (i.e., $s^2 = 2.9704/163 = 0.0182$). The other sums of squares in this column represent a partitioning of the total sum of squares. Note that they sum to the total sum of squares:

$$0.2908 + 2.6796 = 2.9704$$

The calculations for these other sums of squares are somewhat more involved than the total sum of squares and will not be discussed here. The interested reader can find details of these calculations in Iman, 1994.

Mean Square. The values in this column are obtained by dividing the sum of squares in each row by their respective degrees of freedom:

Mean Square for Site/Flux $= 0.2908/22 = 0.0132$
Mean Square for Error $= 2.6796/141 = 0.0190$

The Mean Square Error calculation is an estimate of the standard error for the experiment. Note that this estimate (0.0190) differs from the sample variance (0.0182), as the standard error is computed after the other source of variation in the data (Site/Flux) has been taken into account. Note that these two variance estimates are close in this particular example, but they can differ greatly.

F-Statistic. This column contains the f-statistic that is used to determine if Site/Flux makes a statistically significant contribution to the total variation. The f-statistic is the ratio of the Mean Square for Site/Flux and Mean Square Error:

F-statistic = (Mean Square Site/Flux)/(Mean Square Error) = 0.0132/0.0190 = 0.70

In the surface finishes analysis, when the f-statistic was significant, the Least Significant Difference (LSD) procedure (described below) was used to compare the means of the 23 site/flux combinations given in Table 4-3, and results are displayed in boxplots (also described below).

P-Value. The statistical significance of the f-statistic (the p-value) is given in the last column of the ANOVA table. This value is determined by comparing the f-statistic to its probability distributions (the larger the f-statistic, the more significant the contribution). Probability distributions for f-statistics are indexed by two parameters known as degrees of freedom. The degrees of freedom for the f-statistic are Site/Flux DF = 22 and Error DF = 141. The p-value is computed as the tail probability for the f-statistic as:

P-Value = $\text{Prob}(F_{22,141} > F_{\text{site/Flux}})$ = $\text{Prob}(F_{22,141} > 0.70)$ = 0.838

Whenever a p-value in this analysis is less than 0.01, the corresponding source of variation can be regarded as making a significant contribution to the overall variation. In this example the p-value is quite large, which signifies that Site/Flux does not make a significant contribution to the overall variation in the data. Thus, there is no need to check for differences in the means of the site/flux combinations. In statistical analyses, the level of significance frequently is a p-value less than 0.05. The more stringent 0.01 is used in this report because of the relatively small cell sizes (4 or 8 samples per circuit per site/flux combination) and the potentially important decisions that may be made based on these test results.

Least Significant Difference. In the event that the p-values associated with the F-statistics are less than 0.01, the sample means can be incorporated into a test statistic for determining which population means are significantly different from one another. The "measuring stick" used to compare the sample means is known as Fisher's LSD. In particular, two population means are declared significantly different from one another if the absolute difference of the corresponding sample means exceeds LSD_a, which is defined as:

$$LSD_\alpha = t_{\alpha/2, n-k} \sqrt{MSE} \sqrt{\frac{1}{n_i} + \frac{1}{n_j}}$$

where,

α	=	level of significance
t	=	the α/2 quantile from a Student's t distribution with *n-k* degrees of freedom
MSE	=	mean square error for the model
n_i and n_j	=	sample sizes for the means being compared

When the F-statistic is significant, the LSD procedure will be used to compare the means of the 23 site/flux combinations given in Table 4-3. Results of the multiple comparisons will be displayed in boxplots (described below).

Table 4-3. Listing of 23 Site/Flux Combinations Used in the Multiple Comparisons Analyses

| Site/Flux Combination	Surface Finish	Flux Type	Site No.	No. of Observations
1	HASL	LR	1	8
2	HASL	WS	1	8
3	HASL	LR	2	8
4	HASL	WS	3	8
5	OSP	LR	4	4
6	OSP	WS	4	8
7	OSP	LR	5	8
8	OSP	WS	5	8
9	OSP	LR	6	8
10	Immersion Tin	LR	7	4
11	Immersion Tin	WS	7	8
12	Immersion Tin	LR	8	8
13	Immersion Tin	LR	9	8
14	Immersion Tin	WS	10	8
15	Immersion Silver	LR	11	8
16	Immersion Silver	WS	11	4
17	Immersion Silver	WS	12	8
18	Nickel/Gold	LR	13	4
19	Nickel/Gold	WS	13	8
20	Nickel/Gold	LR	14	8
21	Nickel/Gold	WS	15	8
22	Nickel/Palladium/Gold	LR	16	8
23	Nickel/Palladium/Gold	WS	16	4

LR = low residue; WS = water soluble.

Boxplot Displays

A boxplot is simply a rectangular box with lines extending from the left-hand and right-hand sides of the box as shown below. The left-hand side of the box represents the lower quartile ($X_{.25}$) or lower 25 percent of the sample data. The right-hand side of the box represents the upper quartile ($X_{.75}$), or upper 25 percent of the sample data (or lower 75 percent). Thus, the box covers the middle 50 percent of the sample data. A vertical line inside the box connecting the top and bottom sides represents the sample median ($X_{.50}$).

The interquartile range (IQR) is the difference between the upper quartile and the lower quartile. A horizontal line at the right-hand side of the box extends to the maximum observation in the interval from $X_{.75}$ to $X_{.75}$ + 1.5 IQR. This line never extends beyond $X_{.75}$ + 1.5 IQR. A horizontal line on the left-hand side extends to the smallest observation between $X_{.25}$ and $X_{.25}$ - 1.5 IQR. This line never extends below $X_{.25}$ - 1.5 IQR. Any observations outside of these limits are regarded as outliers and are marked with an asterisk or other symbols. A heavy dot is frequently added to a boxplot to identify the sample mean.

Boxplots can be constructed in either a horizontal or vertical position. When the boxplot is constructed vertically, the top side of the box represents the upper quartile and the bottom side represents the lower quartile.

Boxplot displays have advantages over traditional plots of means, such as: 1) the median is not heavily influenced by outlying or unusual observations that can be misleading; and 2) the information about the variability in the data, captured in a boxplot, is lost in a plot of the means. Boxplots will be used as the basis for graphical displays of the multiple comparisons results for each electrical response for each test.
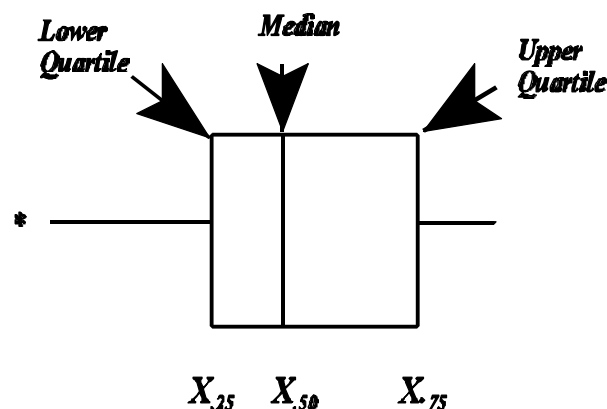
A Boxplot Used to Display Test Results

4.1.6 Overview of Test Results

The 164 PWAs as summarized in Table 4-2 were functionally tested at the following four times:

- Pre-test;
- Post-85/85;
- Post-TS; and
- Post-MS.

At each of these test times, 3,772 electrical test measurements were recorded (164 PWAs $\times$ 23 individual circuits). An overall summary of success rates based on 3,608 measurements[1] at each test time is shown in Table 4-4.

Table 4-4. Number of Anomalies Observed at Each Test Time

Test Time	Anomalies	Success Rate
Pre-test	2	99.9%
Post-85/85	17	99.6%
Post-TS	113	96.9%
Post-MS	527	85.4%

MS = mechanical shock.; TS = thermal shock.

An overview of the test results at each test time is discussed in this section. A discussion of the results for each test time for each major circuit group is presented in Sections 4.1.7 through 4.1.13. An overview of the circuits meeting the acceptance criteria after each testing sequence is summarized in Table 4-5 for each major circuit group.

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[1] Since HF TLC RNF gave a constant response of 50MHz throughout, there is no variability to analyze.

Table 4-5. Percentage of Circuits Meeting Acceptance Criteria at Each Test Time [2]

Circuitry	85/85	Thermal Shock	Mechanical Shock
HCLV	100%	100%	48.2% (7.1% SMT)
HVLC	99.7%	99.7%	50.0% (0.0% SMT)
HSD	99.7%	98.8%	99.1% (99.3% SMT)
HF LPF	98.7%	89.4%	82.6% (74.8% SMT)
HF TLC	99.8%	99.5%	97.9%
Other Networks	99.8%	100%	100%
SW	100%	99.7%	98.5%
Totals	**99.5%**	**96.9%**	**85.4%**

HCLV = high current low voltage; HF LPF = high frequency low pass filter; HF TLC = high frequency transmission line coupler; HSD = high speed digital; HVLC = high voltage low current; SMT = surface mount technology; SW = stranded wire.

Overview of Pre-Test Results

The electrical measurements were compared to the acceptance criteria given in Table 4-1 at each test time. Note that the acceptance criteria require a comparison to pre-test results for all but six of the 23 electrical circuits (#'s 3, 4, 18-21 in Table 4-1). Hence, pre-test comparisons to the acceptable criteria can only be made for those six circuits. There were no pre-test anomalies observed for those six circuits. Pre-test measurements for the remaining 17 circuits were compared to CCAMTF pre-test results. Table 4-6 presents this comparison of the ranges of the measurements for each of the 23 circuits with pre-test measurements for the PWAs used in the CCAMTF 85/85 testing.

Table 4-6 shows that the two sets of ranges for circuits 5 through 12 and 16 do not even overlap. The lack of overlap in the ranges for the HSD PTH and HSD SMT circuits (#'s 5 and 6) is due to different components being used on the DfE PWAs than were used in processing the PWAs in the CCAMTF program. The differences in the HF LPF circuits 7 through 12 are more difficult to pinpoint. The most likely explanation lies in the fact that the actual boards used in the DfE program and those in the CCAMTF PWAs were produced by two different manufacturers. FR-4 epoxy was used for the board laminate material. HF LPF responses are sensitive to the dielectric constant of the board laminate material. Differences in FR-4 epoxy at the two manufacturing locations used by the DfE program and the CCAMTF program could have affected the dielectric constant and hence the HF LPF responses. Another possibility is that the board layers manufactured at the two locations might not be the same thickness. A microsection was required to make this determination, which was beyond the scope of this analysis. A final possibility is that the two sets of boards might have used a different lot of ceramic capacitors, but this is not likely, as all the parts for the DfE and CCAMTF boards were ordered at the same time.

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[2] The total number of measurements, rather than the number of measurements meeting the acceptance criteria after the previous test, is used to calculate these percentages. While it is possible to adjust for anomalies resulting from the previous test, doing so: 1) would make the calculation conditional on the previous test and therefore would require a very careful interpretation ; and 2) would not reflect the "curing" that can occur with a circuit that is an anomaly in one test but meets the acceptance criteria in the subsequent test.

Table 4-6. Comparison of CCAMTF Pre-Test Ranges with DfE Pre-Test Measurements

Circuit [units]	CCAMTF Pre-Test		DfE Pre-Test	
	Min	Max	Min	Max
1 HCLV PTH [V]	6.60	7.20	6.80	7.52
2 HCLV SMT [V]	6.96	7.44	7.00	7.44
3 HVLC PTH [μA]	5.00	5.25	5.00	5.25
4 HVLC SMT [μA]	4.92	4.97	4.81	5.39
5 HSD PTH Propagation Delay [μ sec]	12.66	13.50	16.76	18.20
6 HSD SMT Propagation Delay [μ sec]	4.28	5.45	8.89	9.52
7 HF PTH 50MHz [dB]	-0.320	0.094	-1.176	-0.365
8 HF PTH f (-3dB) [MHZ]	239.4	262.6	274.4	287.5
9 HF PTH f (-40dB) [MHZ]	425.3	454.9	456.7	485.2
10 HF PTH 50MHz [dB]	-0.296	0.081	-0.901	-0.617
11 HF SMT f (-3dB) [MHZ]	275.0	283.3	313.0	338.0
12 HF SMT f (-40dB) [MHZ]	642.6	674.0	811.2	951.9
13 HF TLC 50MHz Forward Response [dB]	-49.74	-36.48	-50.87	-42.66
14 HF TLC 500MHz Forward Response [dB]	-21.47	-17.54	-19.91	-15.28
15 HF TLC 1GHz Forward Response [dB]	-16.91	-12.08	-15.01	-12.89
16 HF TLC Reverse Null Frequency [MHZ]	624.2	659.8	50.0	79.7
17 HF TLC Reverse Null Response [dB]	-74.53	-38.22	-43.67	-32.08
18 10-mil Pads [log$_{10}$ ohms]	10.01	15.00	10.10	15.00
19 PGA-A [log$_{10}$ ohms]	8.94	15.00	10.38	14.00
20 PGA-B [log$_{10}$ ohms]	8.72	15.00	10.07	13.70
21 Gull Wing [log$_{10}$ ohms]	9.71	14.00	9.01	13.70
22 SW 1 [mV]	5	19	7	19
23 SW 2 [mV]	19	28	19	28

HCLV = high current low voltage; HF = high frequency; HSD = high speed digital; HVLC = high voltage low current; PGA = pin grid array; PTH = plated through hole; SMT = surface mount technology; SW = stranded wire; TLC = transmission line coupler.

The reverse response function (#16 in Table 4-6) provides a range of responses from 50MHz to 1GHz. The low point of this curve is referred to as the null point. The coordinates of the null point are the HF TLC Reverse Null Frequency (in MHZ) and HF TLC Reverse Null Response (in dB). The HF TLC Reverse Null Frequency ranged from approximately 624MHz to 660MHz in the CCAMTF program, while the HF TLC Reverse Null Response ranged from approximately -75dB to -38dB. However, the null point of the reverse response function for the DfE PWAs occurred at the beginning of the curve, which is approximately 50MHz. In fact, all but two of the HF Reverse Null Frequency measurements were 50MHz with the others being 77.3MHz and 79.7MHz. The Reverse Null Response ranged from -43.7dB to -32.1dB. The nearly constant value of HF Reverse Null Frequency relegates any subsequent analysis of the uncertainty to a moot point. As discussed further in subsequent sections, none of the discrepancies could be attributed to the performance of the surface finishes.

Overview of 85/85 Results

At the conclusion of the 85/85 test, 99.5% of the electrical measurements met the acceptance criteria given in Table 4-1. There were 17 anomalies distributed across 10 PWAs, as shown in Table 4-7. Among the PWAs with anomalies, five were assembled with the low-residue flux and five were assembled with the water-soluble flux. The anomalies are summarized in Appendix F, Table F-1. Table F-1 also contains observations made by the testing technician that are useful in identifying the source of the anomaly for those cases where a problem was obvious, such as an open PTH, a burnt etch, or a failed device.

Table 4-7. Frequency Distribution of Post-85/85 Anomalies per PWA by Surface Finish
(Sample sizes are given in parentheses)

Number of Anomalies per PWA	HASL (32)	Nickel/Gold (28)	Nickel/Palladium/Gold (12)	OSP (36)	Immersion Silver (20)	Immersion Tin (36)
None	31	26	12	35	18	32
1		2			1	3
2						1
3	1			1	1	
Total Anomalies	**3**	**2**	**0**	**3**	**4**	**5**

Overview of Thermal Shock Results

The number of anomalies increased from 17 at the post-85/85 test to 113 at the post-TS test, so that 96.9% of the electrical measurements met the acceptance criteria given in Table 4-1. Of the 17 anomalies at post-85/85, 16 carried over to post-TS, so that the thermal shock test introduced 97 new anomalies. 91% of the post-TS anomalies occurred for HF LPF circuits. As shown in Table 4-8, the 113 anomalies affected 42 PWAs, with 19 PWAs accounting for 88 of the anomalies. Of the PWAs with anomalies, 16 were assembled with low residue flux and 26 were assembled with water soluble flux. The anomalies are summarized by surface finish in Appendix F, Table F-2. This summary includes several observations made by the testing technician that are useful in identifying the source of the anomaly.

A chi-square test of independence (Iman, 1994) indicates that the anomalies are not uniformly distributed over the surface finishes, with immersion silver and immersion tin having more than expected. The p-value for this test is 0.025. The chi-square test does not indicate a difference in anomalies with respect to flux type.

**Table 4-8. Frequency Distribution of Post-Thermal Shock Anomalies per PWA
by Surface Finish**
(Sample sizes are given in parentheses)

Number of Anomalies per PWA	HASL (32)	Nickel/Gold (28)	Nickel/Palladium/Gold (12)	OSP (36)	Immersion Silver (20)	Immersion Tin (36)
None	25	25	11	28	11	22
1	4	1	1	2	2	3
2				3		3
3	2	2		2	3	5
4					1	3
5						
6	1			1	3	
Total Anomalies	**16**	**7**	**1**	**20**	**33**	**36**

Overview of Mechanical Shock Results

The number of anomalies increased greatly from 113 at post-TS to 527 at post-MS. 85% of the electrical measurements met the acceptance criteria given in Table 4-1. Of the 113 anomalies at post-TS, 97 carried over to post-MS, hence the mechanical shock test introduced 430 new anomalies. Theses new anomalies included 157 from HCLV SMT — in contrast, there was only one HVLC SMT anomaly at post-TS. In addition, there were 163 new anomalies from the HVLC SMT circuits. Thus, these two circuits accounted for 320 of the 430 new anomalies. The anomalies for these two SMT circuits were attributable to SMT components coming off the board during the execution of the mechanical shock test. This affected every board and has no relation to site, surface finish, or flux.

All anomalies, except for those associated with HCLV SMT and HVLC SMT (since these affected every PWA), are summarized in Appendix F, Table F-3. In addition, this table includes comments made by the test technician. There were five minor stranded wire anomalies that are not listed in Table F-3.

At post-MS, every PWA had at least one anomaly. Table 4-9 provides a breakdown of the number of anomalies per PWA for each surface finish. The last row in this table gives the median number of anomalies per PWA for each surface finish. The hypothesis that the mean number of anomalies is the same for all surface finishes is easily rejected with a p-value of 0.000 based on the Kruskal-Wallis test (Iman, 1994). Immersion silver has the most anomalies per PWA with nickel/gold and nickel/palladium/gold having the least. HASL and OSP had approximately the same number of anomalies, with immersion tin slightly higher than these two. The following section provides insight on the source of the anomaly disparities relative to surface finish.

Table 4-9. Frequency Distribution of Post-Mechanical Shock Anomalies per PWA by Surface Finish
(Sample sizes are given in parentheses)

Number of Anomalies per PWA	HASL (32)	Nickel/Gold (28)	Nickel/Palladium/Gold (12)	OSP (36)	Immersion Silver (20)	Immersion Tin (36)
none						
1	1	1				
2	16	20	11	14	5	12
3	8	5	1	14	5	11
4		1		3		2
5	5	1		3	3	3
6					2	6
7					2	1
8	2			2		1
9					1	
10					2	
Total Anomalies	**98**	**65**	**25**	**113**	**95**	**131**
Median	**2**	**2**	**2**	**3**	**4**	**3**

4.1.7 HCLV Circuitry Performance Results

Pre-test measurements and deltas were analyzed with GLM for the main effects of site and flux and their interactions, where the base case was defined as HASL at Site l and processed with low residue flux. These data were also subjected to a second GLM analysis for the main effects of surface finish and flux, where the base case was defined as HASL processed with low residue flux. The specific equations used for these two analyses are given in Appendix F as Equation F-1 and F-2, respectively.

The results of the GLM analyses indicate that the experimental parameters surface finish, site, and flux do not significantly affect the HCLV voltage measurements at pre-test, nor do they affect the changes in the voltage after exposure to each of the three test environments. That is, the HCLV measurements are robust with respect to surface finish, site, and flux. The results for the two GLMs used in the analysis are examined in more detail in Appendix F.

Multiple comparison procedures for comparing the means of the 23 site/flux combinations given in Table 4-3 were explained previously. The overall ANOVA that precedes the use of multiple comparisons produced a significant f-statistic only at post-MS for HCLV PTH. The HCLV SMT was close to significance at post-TS with a p-value of 0.018, as shown in Table 4-10 (non-significant values > 0.0 l have been shaded).

Table 4-10. P-Values for HCLV Test Results

Test Time	P-Value for HCLV PTH	P-Value for HCLV SMT
Pre-test	0.838	0.442
Post-85/85	0.953	0.109
Post-TS	0.496	0.018
Post-MS	0.001	0.861

HCLV = high current low voltage; MS = mechanical shock; PTH = plated through hole; SMT = surface mount technology; TS = thermal shock.

Boxplot Displays of Multiple Comparison Results. Boxplot displays provide a convenient way to display multiple comparison results. Multiple comparison procedures are only justified for HCLV PTH at post-MS since the other f-statistics were not significant. However, boxplot displays are given in Figure 4-1 to 4-8 for all HCLV circuits for purposes of comparison. Figures 4-1 to 4-4 display the test results at each test time for HCLV PTH circuits and Figures 4-5 to 4-8 do the same for HCLV SMT circuits. For improved readability, all boxplots referenced in this chapter can be found in Section 4.1.16 at the end of the performance results discussion. Additional boxplots, where findings were not significant, can be found in Appendix F.

Some explanation of the contents of each graph of boxplots should facilitate understanding. The test time and circuit type are labeled in the upper left-hand corner of each boxplot display. The numbers (1 to 23) on the horizontal axis in each figure correspond respectively to the 23 site/flux combinations listed in Table 4-3. The label WS on the horizontal axis signifies those demonstration sites for which water soluble flux was used; otherwise, the flux type was low residue (LR). The boxplots are grouped by surface finish, which are identified with labels across the top of each graph. At pre-test, the vertical axis corresponds to the absolute test measurement. After pre-test, the vertical axis either corresponds to the absolute test measurement or the difference from the pre-test measurement as specified in the acceptance criteria. The sample mean is identified in each boxplot with a solid circle

Note that there is a lot of overlap in all boxplots in Figure 4-1, which is consistent with the lack of significance in the f-statistics for equality of means and in the results for the GLMs. Also note that the total variation in the boxplots is approximately 0.3V, which most likely is not of concern. Figures 4-2 to 4-4 display the differences between the current HCLV PTH measurements and those obtained at pre-test. Note that all differences in Figures 4-2 and 4-3 are well below the acceptance criteria of $\Delta V < 0.5V$. However, several of the differences are well above the acceptance criteria following mechanical shock, as illustrated in Figure 4-4. The significant difference in means in Figure 4-4 at post-MS is attributable mostly to immersion silver at Site 17 processed with a water soluble flux. It should be noted, however, that the other two immersion silver sites showed no anomalies. This may indicate a site-specific problem and not a surface finish problem. Additional failure analysis would be needed to draw further conclusions.

Figures 4-5 to 4-8 are similar to those for HCLV PTH. Figure 4-8 for the HCLV SMT circuit is especially worthy of note as it reflects the increase in voltage due to the loss of one or two resistors (as illustrated in detail in Equations 2.1 to 2.3 in Appendix F). The loss of resistors has caused an increase in voltage of 2V to 3V, which exceeds the acceptance criteria.

Comparison to Acceptance Criteria. The acceptance criteria for HCLV PTH and HCLV SMT (responses 1 and 2 in Table 4-1) are based on the following differences between test measurements:

Delta 1   =   85/85 - pre-test
Delta 2   =   thermal shock - pre-test
Delta 3   =   mechanical shock - pre-test

Specifically, these differences are not to exceed 0.50V.

None of the HCLV PTH or HCLV SMT voltage measurements exceeded the acceptance criterion of $\Delta V < 0.50V$ after exposure to 85/85 or thermal shock. However, following mechanical shock there were 12 HCLV PTH anomalies and 158 HCLV SMT anomalies. Whereas the HCLV SMT anomalies affected almost every PWA, the HCLV PTH anomalies were distributed unevenly among surface finishes, as shown in Table 4-11.

Table 4-11. Number of HCLV PTH Anomalies at Post-Mechanical Shock by Surface Finish

Surface Finish	Anomalies	No. of PWAs
HASL	1	32
Nickel/Gold	0	28
Nickel/Palladium/Gold	0	12
OSP	3	36
Immersion Silver	5	20
Immersion Tin	3	36

4.1.8 HVLC Circuitry Performance Results

Results of the GLM analyses for HVLC PTH and HVLC SMT circuits are given in Tables F-6 and F-7, respectively. The GLM analyses show no practical significance relative to the acceptance criteria, which indicates that site, flux, and surface finish parameters do not influence the HVLC measurements.

Unlike the resistors in the HCLV circuit that were in a parallel design, the HVLC resistors were in a series circuit design. Thus, when one resistor is missing the circuit is open.

Boxplot Displays of Multiple Comparison Results. The overall ANOVA that precedes the use of multiple comparisons did not produce significant f-statistics for HVLC PTH (level of significance = 0.01). However, it did produce significant f-statistics for the first three test times for the HVLC SMT circuit, as shown in Table 4-12 (shaded entries are > 0.01).

Table 4-12. P-Values for HVLC Test Results

Test Time	P-Value for HVLC PTH	P-Value for HVLC SMT
Pre-test	0.046	0.000
Post-85/85	0.028	0.000
Post-TS	0.625	0.000
Post-MS	0.274	0.742

HCLV = high current low voltage; MS = mechanical shock; PTH = plated through hole; SMT = surface mount technology; TS = thermal shock.

Figures F-1 to F-8 give boxplots for the HVLC PTH and SMT circuits. It is important to keep the vertical scale in mind relative to the acceptance criteria when viewing these boxplots. That is, the acceptance criteria indicates that the current should be between $4\mu A$ and $6\mu A$. These boxplots are centered close to $5\mu A$, and the total spread is on the order of $0.02\mu A$ for the PTH circuits and approximately $0.5\mu A$ for SMT circuits. Hence, even though there are some statistically significantly differences, they are not likely to be of practical concern. Note the boxplots in Figure F-8 for HCLV SMT at post-MS. These values are all either $0\mu A$, or very close to it, reflecting the fact that the resistors came off the PWA during the mechanical shock test. This loss of components occurred on every PWA and was not related to the site, surface finish, or flux.

Comparison to Acceptance Criterion. The acceptance criteria for HVLC PTH and HVLC SMT are listed in Table 4-1 (responses 3 and 4). All HVLC PTH circuits met the acceptance criteria of $4\mu A$ and $6\mu A$ for the entire sequence of tests. Only one HVLC SMT current measurement failed to meet the acceptance criterion after exposure to 85/85 (see Table F-1). In turn, this same PWA also was the only one that did not meet the acceptance criteria after thermal shock. The test technician noted that this PWA exhibited a burnt edge after 85/85. However, after the mechanical shock test all HVLC SMT circuits failed to meet the acceptance criteria due to resistors coming off the PWA resulting in an open circuit.

4.1.9 High Speed Digital Circuitry Performance Results

The pre-test measurements for HSD PTH and HSD SMT circuits were subjected to GLM analyses, as were the deltas after 85/85, thermal shock, and mechanical shock. The complete results of the GLM analyses are given in Tables F-8 and F-9, respectively. The GLM analyses indicate that the experimental parameters under evaluation do not influence the HSD total propagation delay measurements.

Boxplot Displays of Multiple Comparison Results. The overall ANOVA that precedes the use of multiple comparisons did not produce significant f-statistics for either HSD PTH or HSD SMT circuitry. The p-values for the respective f-statistics are given in Table 4-13 (shaded entries are > 0.01).

Table 4-13. P-Values for HSD Test Results

Test Time	P-Value for HSD PTH	P-Value for HSD SMT
Pre-test	0.442	0.585
Post-85/85	0.443	0.359
Post-TS	0.491	0.954
Post-MS	0.487	0.760

HSD = high speed digital; MS = mechanical shock; PTH = plated through hole; SMT = surface mount technology; TS = thermal shock.

Figures F-9 and F-10 give boxplots of pre-test measurements of total propagation delay for the HSD PTH and HSD SMT circuits, respectively. Note that most total propagation delays in Figure F-9 for HSD PTH are a little over 17 nanoseconds (ns) with a range of about 1ns. Figure F-10 shows that the total propagation delays for HSD SMT have a range of about 0.4ns and are centered about 9.2ns. The percentage changes in the total propagation delay measurements were small and well within the acceptance criteria so boxplot displays of these measurements are not presented.

Comparison to Acceptance Criterion. The acceptance criteria for HSD PTH and HSD SMT are listed in Table 4-1 (responses 5 and 6). One HSD SMT did not give a response after exposure to 85/85 (see Table F-1). This same circuit also failed to give a response after thermal shock, as did one additional HSD SMT circuit and two HSD PTH circuits. At post-MS, two HSD PTH circuits and one HSD SMT circuit did not give a response. The testing technician indicated that the HSD device had failed. Previous testing with the test PWA in other programs has indicated a failure of the HSD components, which is independent of the experimental parameters under evaluation in the DfE program. All other HSD circuits were well within the acceptance criterion.

4.1.10 High Frequency Low Pass Filter Circuitry Performance Results

Pre-test measurements for all HF LPF circuits were subjected to GLM analyses, as were the deltas after 85/85, thermal shock, and mechanical shock. The results of the GLM analyses are given in Tables F-10 to F-15. The GLM analyses indicate that the parameters under evaluation (site, surface finish, or flux) do not influence the HF LPF measurements. The same is true at post-85/85, post-TS and post-MS. However, the test measurements contained many extreme outlying observations at both of these later two test times, which greatly increases the sample variance and in turn hinders the interpretation of the GLM results. As indicated in Tables F-1, F-2, and F-3 there were many anomalous HF LPF test measurements (171 at post-MS). The principal source of these outliers was open PTHs, is discussed in more detail under *Comparison to Acceptance Criteria.*

Boxplot Displays of Multiple Comparison Results

The ANOVA that precedes the use of multiple comparisons produced significant f-statistics for HF LPF PTH 50MHz at all test times and for three other HF LPF circuits at post-TS. The p-values for the respective f-statistics are given in Table 4-14 (all p-values > 0.01 are shaded).

Table 4-14. P-Values for HF LPF Test Results

Test Time	P-Value for HF PTH 50MHz	P-Value for HF PTH f(-3dB)	P-Value for HF PTH f(-40dB)	P-Value for HF SMT 50MHz	P-Value for HF SMT f(-3dB)	P-Value for HF SMT f (-40dB)
Pre-test	0.002	0.052	0.024	0.241	0.092	0.057
Post-85/85	0.000	0.484	0.487	0.227	0.258	0.970
Post-TS	0.004	0.578	0.594	0.016	0.074	0.023
Post-MS	0.002	0.001	0.028	0.000	0.112	0.000

HF = high frequency; LPF = low pass filter; MS = mechanical shock; PTH = plated through hole; SMT = surface mount technology; TS = thermal shock.

These results are discussed separately for each of the six HF LPF circuits. Boxplot displays of all test results for HF LPF circuits have been created to aid in the interpretation. Only the boxplots showing statistical and practical significance are shown here (Figures 4-9 to 4-15); the rest are in Appendix F.

HF LPF PTH 50MHz. While the p-values for the associated f-statistic were highly significant at all test times, Figure 4-9 identifies the source of this significance at pre-test, where the responses for nickel/gold applied at Site 18 and subsequently processed with low residue flux are much lower than the others. Post-85/85 and post-TS results indicate just the opposite for this demonstration site (see Figures F-11 and F-12). What occurred is that the problem circuit returned to normal at post-85/85 and post-TS, but those measurements were then compared to their low pre-test measurements, which caused the differences to be large in the positive direction. Hence, the significance at post-85/85 and post-TS are an artifact of the pre-test measurements and should most likely be ignored as the circuit performance was in line with all others. More importantly, the significant differences at pre-test are too small to be of practical concern. The range depicted in Figure 4-9 is approximately 0.7dB and the acceptance criterion allows a change of $\pm$5dB. On the other hand, Figure 4-10 is of concern as several of the surface finishes have measurements well below the lower bound acceptance criterion of -5dB. In particular, one of the five OSP PWAs, two of the three immersion silver PWAs, and one of the five immersion tin PWAs. This circuit had 15 anomalies at post-MS.

HF LPF PTH f(-3dB). Figure 4-11 shows the boxplot for the HF LPF PTH f(-3dB) circuit at the post-MS test time. Boxplots for the other three test times can be found in Appendix F, since the p-values for the associated F-statistic were not significant, except for post-MS. Figure 4-11 shows notable variation in the magnitude of the differences — note the vertical scale. Several cases are well outside the acceptance criterion. In particular, one of four nickel/gold PWAs, two of the three immersion silver PWAs, and one of five immersion tin PWAs are quite low. This circuit had 18 anomalies at post-MS.

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HF LPF PTH f(-40dB). Figure 4-12 shows the boxplot for the HF LPF PTH f(-40dB) circuit at the post-MS test time. Boxplots for the other three test times can be found in Appendix F. While the p-values for the associated f-statistic were not significant at any of the test times, Figure 4-12 shows notable variation in the magnitude of the differences (note the vertical scale). Several cases are well outside the acceptance criterion of $\pm$50MHz. In particular, two of the three immersion silver PWAs and one of five immersion tin PWAs are quite low. This circuit had 14 anomalies at post-MS.

HF LPF SMT 50MHz. Figure 4-13 shows the boxplot for the HF LPF SMT 50MHz circuit at the post-MS test time. Boxplots for the other three test times can be found in Appendix F, since the p-values for the associated f-statistic were not significant, except for post-MS. The magnitude of the changes at post-85/85 and post-TS are too small to be of practical concern relative to the acceptance criteria of $\pm$5dB. On the other hand, the post-MS results are of serious concern, as nine of 23 cases are well below the lower acceptance bound of -5dB. It is noteworthy that neither nickel/gold or nickel/palladium/gold had any anomalies. This circuit had 30 anomalies at post-MS.

HF LPF SMT f(-3dB). Figure 4-14 shows the boxplot for the HF LPF SMT f(-3dB) circuit at the post-MS test time. Boxplots for the other three test times can be found in Appendix F. While the p-values for the associated F-statistic were not significant at any of the test times, Figure 4-14 shows notable variation in the magnitude of the differences (note the vertical scale). Several cases are well outside the acceptance criterion of $\pm$50MHz. It is noteworthy that neither nickel/gold or nickel/palladium/gold had any anomalies. This circuit had 29 anomalies at post-MS.

HF LPF SMT f(-40dB). Figure 4-15 shows the boxplot for the HF LPF SMT f(-40dB) circuit at the post-MS test time. Boxplots for the other three test times can be found in Appendix F, since the p-values for the associated f-statistic were not significant, except at post-MS. This circuit had the most anomalies (65) at post-MS. Some of the anomalies may be due to the high variability in the frequency when measured at -40dB. Figure 4-15 shows notable variation in the magnitude of the differences (note the vertical scale). Most cases are well outside the acceptance criterion of $\pm$50MHz. Nickel/gold and nickel/palladium gold are again noteworthy as they have very few anomalies.

Comparison to Acceptance Criteria

The acceptance criteria for the six HF LPF circuits are shown I Table 4-1 (responses 7 through 12). Thirteen of 984 HF LPF test measurements did not meet the acceptance criterion after exposure to 85/85 (see Table F-1). These 13 responses occurred on six PWAs, with 12 of the 13 occurring with PTH components. After exposure to thermal shock, the number of HF LPF anomalies increased to 104 (see Table F-2). Thirteen of these 103 HF LPF anomalies carried over from the 85/85 test. At post-MS, the number of anomalies increased to 171 with 97 carrying over from thermal shock.

PWAs with HF LPF anomalies generally have multiple anomalies. This can be seen in Table 4-15, which shows the frequency distribution of the number of HF LPF anomalies per PWA at post-MS (see Tables F-1 to F-3).

Table 4-15. Frequency Distribution of HF LPF Anomalies at Post-Mechanical Shock per PWA

No. of HF LPF Anomalies per PWA at Post-Mechanical Shock	Frequency
None	90
1	36
2	5
3	20
4	4
5	5
6	4

The test technician comments indicate that most of the HF LPF anomalies were due to an open PTH, which affects both PTH and SMT. To explain further, a circuit board consists of alternating layers of epoxy and copper through which a hole is drilled during fabrication. This via is plated with a very thin layer of electroless copper to provide a "seed bed" for the primary coatings. Copper is then electroplated over the electroless copper strike. The final surface finish (HASL, OSP, etc.) is then applied. Failure to make an electrical connection between the copper etches on the opposite sides of the board is known as an open PTH. The opens occurred in very small vias in the HF LPF circuit. Small vias can be very difficult to plate. Opens were present during in-circuit testing and at pre-test. In some cases, a z-wire was inserted through the via to make an electrical connection between the etches on the opposite side of the board. It appears that test conditions may accelerate the problem.

Although an open PTH is a fabrication issue, there does appear to be a relationship with surface finish. The HF LPF anomalies are summarized by surface finish in Table 4-17 for each of the six HF LPF circuits. Under the assumption that the anomalies occur independent of surface finish, the expected number of anomalies can be calculated for each cell. For example, consider Table 4-16, which summarizes the observed and expected anomalies for the HF LPF PTH 50MHz circuit.

Table 4-16. Comparison of the Observed and Expected Number of Anomalies for the HF LPF PTH 50MHz Circuit by Surface Finish

Surface Finish	Observed Anomalies (Expected)	Observed Non-Anomalies (Expected)	Row Total
HASL	1 (2.9)	31 (29.1)	32
Nickel/Gold	2 (2.6)	26 (25.4)	28
Nickel/Palladium/Gold	0 (1.1)	12 (10.9)	12
OSP	2 (3.3)	34 (32.7)	36
Immersion Silver	6 (1.8)	14 (18.2)	20
Immersion Tin	4 (3.3)	32 (32.7)	36
Column Total	**15**	**149**	**164**

HF = high frequency; LPF = low pass filter; PTH = plated through hole**.**

Under the hypothesis of independence of row and column classifications, the expected number of observations in each cell is the product of the cell's row and column totals divided by the grand total. For example, the expected number of anomalies for HASL is computed as (32)(15)/164 = 2.9. The expected values for all cells are shown in parentheses in the example. A chi-square statistic is calculated on the differences of the observed and expected number in each cell (Iman, 1994). The chi-square distribution is used to approximate the p-value for the chi-square statistic. For the above example, the p-value is 0.016, which is not significant at the 0.01 level. With this level of significance, the hypothesis of independence is not rejected for the HF LPF PTH 50MHz circuit. That is, there are no significant differences in the number of anomalies among the surface finishes for the HF LPF PTH 50MHz circuit.

Table 4-17. Comparison of the Observed and Expected Number of Anomalies Under the Hypothesis of Independence of Surface Finishes

	No. of PWAs	50MHz	HF LPF PTH f(-3dB)	f(-40dB)	50MHz	HF LPF SMT f(-3dB)	f(-40dB)
HASL	32	1 (2.9)	2 (4.1)	1 (2.9)	6 (5.9)	7 (5.9)	15 (13.1)
Nickel/Gold	28	2 (2.6)	3 (3.6)	2 (2.6)	0 (5.1)	0 (5.1)	1 (11.4)
Nickel/Palladium/Gold	12	0 (1.1)	0 (1.5)	0 (1.1)	0 (2.2)	0 (2.2)	1 (4.9)
OSP	36	2 (3.3)	2 (4.6)	1 (3.3)	6 (6.6)	5 (6.6)	20 (14.7)
Immersion Silver	20	6 (1.8)	6 (2.6)	7 (1.8)	7 (3.7)	6 (3.7)	11 (8.2
Immersion Tin	36	4 (3.3)	5 (4.6)	3 (3.3)	11 (6.6)	11 (6.6)	17 (14.7)
Totals	**164**	**15**	**18**	**14**	**30**	**29**	**65**
	p-value	0.016	0.051	0.001	0.006	0.008	0.000

HF = high frequency; LPF = low pass filter; PTH = plated through hole; SMT = surface mount technology**.**

Such is not the case for the last four HF LPF circuits listed in Table 4-17, where the p-values at the bottom of the table indicate that the anomalies are not independent of surface finish. The expected values for anomalies appear in parenthesis in each cell in that table. These comparisons show:

- HASL anomalies are close to the expected values throughout.
- Nickel/gold has far fewer anomalies than expected.
- Nickel/palladium/gold has far fewer anomalies than expected.
- OSP anomalies are close to expected, except for the last column, where they have more anomalies than expected.
- Immersion silver has many more anomalies that expected for all circuits.
- Immersion tin anomalies are close to expected for PTH circuits, but are higher than expected for SMT circuits.

The number of open PTH anomalies may be related to the inherent strength of the metals. Tin and silver are relatively weak; OSP has no metal, while nickel makes the PTH stronger. To determine the relevancy of metal strength to the open PTH anomalies, the HF LPF circuits would need to be subjected to failure analysis to check for copper plating thickness and PTH voids in the vias, as both of these may be problems in small vias. In addition, the chemical removal of copper from the via may be much greater in immersion tin and immersion silver, depending on how they were processed.

4.1.11 High Frequency Transmission Line Coupler Circuitry Performance Results

Pre-test measurements for all HF TLC circuits except Reverse Null Frequency were subjected to GLM analyses, as were the deltas after 85/85, thermal shock, and mechanical shock. The results of the GLM analyses are given in Tables F-16 to F-20. The GLM analyses indicate that the experimental parameters do not influence the pre-test HF TLC measurements, except for those at 50 MHZ. The results for the 50MHz case are examined in further detail.

The predicted response at pre-test for HF TLC 50MHz for the base case (HASL at Site 1 processed with low residue flux) based on the Site & Flux GLM was -47.43dB. The predicted differences from the base case are given in Appendix F in Table F-21. The results show that the demonstration sites that produced nickel/gold and nickel/palladium/gold (# 13 - 16) have predicted increases of less than 3dB. While statistically significant, this change is rather small compared to the base case value and is probably not of practical utility. Overall, some of the demonstration sites differ from the base case by approximately -1.5dB to 2.9dB. These changes again may not have any practical significance, since the important concept is not so much the magnitude of the response, but rather its stability when subject to environmental stress conditions, which is the basis for the acceptance criteria.

The predicted response at pre-test for HF TLC 50MHz for the base case (HASL processed with low residue flux) based on the Surface Finish & Flux GLM was -46.73dB, which is almost identical to that for the Site & Flux GLM. The predicted differences from the base case are given in Appendix F in Table F-22. These predictions are consistent with those in Table F-21, and

show that immersion tin and immersion silver are approximately 1.0dB lower than the base case, and nickel/gold and nickel/palladium/gold are approximately 1 to 2dB higher than the base case. Again, these differences are most likely not of practical utility.

Boxplot Displays of Multiple Comparison Results. The ANOVA that precedes the use of multiple comparisons produced a significant f-statistic for only the HF TLC 50MHz circuit at pre-test. The p-values for the respective f-statistics are given in Table 4-18 (all p-values > 0.01 are shaded).

Table 4-18. P-Values for HF TLC Test Results

Test Time	P-Value for HF TLC 50MHz	P-Value for HF TLC 500MHz	P-Value for HF TLC 1GHz	P-Value for HF TLC RNR
Pre-test	0.000	0.070	0.250	0.418
Post-85/85	0.285	0.111	0.299	0.201
Post-TS	0.344	0.560	0.650	0.770
Post-MS	0.313	0.390	0.568	0.359

HF TLC = high frequency transmission line coupler; MS = mechanical shock; TS = thermal shock.

Boxplot displays of the test results for HF TLC 50MHz are given in Appendix F. While the F-statistic is significant at pre-test, the post-85/85 results show that the changes from the base case are centered about 0dB and well within the acceptance criteria of ±5dB. Thus, while the magnitude of the individual responses at pre-test may or may not be of practical concern in a particular application, the acceptance criteria is focused on the stability of the response when the circuit is subsequently subjected to environmental stress. The post-85/85 and post-TS results confirm that changes in the responses are all acceptable. However, post-MS shows several anomalies (seven by count), as shown in Figure 4-16. Five of these seven anomalies were for immersion silver, while HASL and immersion tin each had one anomaly.

Figure 4-17 displays the boxplot of the test results for HF TLC 500MHz post-MS. The HF TLC 500MHz results for the other test times are quite similar to those for HF TLC 50MHz, and boxplots of these results can also be found in Appendix F. Post-MS results for HF TLC 500MHz had only one slight anomaly compared to seven for HF TLC 50MHz. This anomaly was only -5.22dB, compared to the lower bound of -5dB, so it is of no concern. Boxplots displays for HF TLC 1GHz are not given to conserve space. The total variation at pre-test for HF TLC 1GHz was only 2dB, and there was only one slight anomaly of -5dB at post-MS, which is not of concern.

Figure 4-18 displays the boxplot of the test results for HF TLC RNR post-MS. None of the F-statistics were significant for testing equality of means; boxplots of results from the other three test times can be found in Appendix F. The reader should keep in mind that the decreases in the HF TLC RNR response in Figure 4-18 are favorable outcomes. The acceptance criterion only specifies an upper bound of either 5dBb or 10dB for the increase, depending on the magnitude of the pre-test values. There were five slight anomalies at post-MS, with immersion tin having three, while HASL and immersion silver each had one.

Comparison to Acceptance Criteria. The acceptance criteria for HF TLC circuitry are listed in Table 4-1 (responses 13 to 17). Only one HF TLC RNR measurement failed to meet the acceptance criterion after exposure to 85/85 (see Table F-1). This measurement showed an increase of 10.2dB, which is only slightly above the acceptance criteria of 10dB and not of practical interest. At post-TS, this value was 10.02. One other HF TLC RNR measurement had an increase of 7.93dB at post-TS. All other changes were less than 5dB. One HF TLC 1GHz measurement was just below the lower limit of -5dB at -5.65dB. There were five anomalies at post-MS, none of which were of practical interest.

4.1.12 Leakage Measurements Performance Results

Four features were included in the design of the test PWA to check for current leakage: 10-mil pads, PGA socket (PGA-A, PGA-B), and a gull wing component (responses 18 to 21 in Table 4-1). The PGA hole pattern has four concentric squares that are electrically connected by traces on the top layer of the board. Two leakage current measurements were made: 1) between the two inner squares (PGA-A; and 2) between the two outer squares (PGA-B). Solder mask covers the pattern of the PGA-B, allowing a direct comparison of similar patterns with and without solder mask. Rather than an actual PGA device, a socket was used, because it provides the same soldering connections as a PGA device.

The leakage measurements were subjected to GLM analyses at pre-test and after 85/85, thermal shock, and mechanical shock. The results of the GLM analyses are given in Appendix F (Tables F-23 to F-26).

10-Mil Pads

Tables F-27 and F-28 give the predicted changes from their respective base cases for all leakage measurements at pre-test for the GLMs. Examination of the GLM results for 10-mil pad shows evidence of site-to-site variation and some interaction between site and flux that affects resistance either positively or negatively by up to an order of magnitude. Demonstration sites applying the OSP surface finish (Sites 6, 7, 8, and 9), as well as Sites 10 and 11 with immersion tin, do not differ from the base case when low residue flux is used. When sites are dropped from the GLM and replaced by surface finishes, the results show slight increases in resistance over the base case for OSP, immersion tin, and immersion silver.

The differences from the base case for both GLMs essentially disappear after exposure to the 85/85 test environment. This result is not unusual and may be due to a *cleansing effect* from the 85/85 test environment that removes residues resulting from board fabrication, assembly, and handling. This same phenomenon was observed for the other three leakage circuits.

Boxplot Displays of Multiple Comparison Results. As with the other circuits, an ANOVA was performed to determine if there was a significant difference in the mean leakage measurements for each of the four leakage circuits. The p-values for the respective f-statistics for all four leakage measurements are given in the following summary (all p-values > 0.01 are shaded). Table 4-19 shows significant differences in the means at pre-test and post-85/85 for the 10-mil pads.

Table 4-19. P-Values for Leakage Test Results

Test Time	P-Value for 10-mil Pads	P-Value for PGA-A	P-Value for PGA-B	P-Value for Gull Wing
Pre-test	0.000	0.000	0.000	0.000
Post-85/85	0.000	0.510	0.198	0.551
Post-TS	0.047	0.048	0.026	0.432
Post-MS	0.213	0.125	0.093	0.243

MS = mechanical shock; PGA = pin grid array; TS = thermal shock.

Boxplot displays of the leakage measurements for 10-mil pads are given in Figures 4-19 and 4-20 for pre-test and post-85/85, respectively. Boxplots for post-TS and post-MS are in Appendix F. Figure 4-19 illustrates the impact of flux that was identified as significant in the GLM analyses. Every case with water soluble flux is higher (better) than the corresponding low residue analog. In Figure 4-20, the differences due to flux have disappeared. As mentioned above, this change is likely due to a cleansing effect from the 85/85 test environment, which removed residues resulting from board fabrication, assembly, and handling. The statistical significance of the F-statistic at post-85/85 is attributable to immersion tin produced at Site 13, which had lower resistance (i.e. higher current leakage). However, the resistance is still well above the acceptance criteria of 7.7.

Comparison to Acceptance Criterion. The acceptance criterion for the leakage measurements requires the resistance to be greater than 7.7 when expressed as log l0 ohms. There were no anomalies for the 10-mil pads at pre-test, post-85/85, post-TS, or post-MS.

Pin Grid Array-A

Examination of the GLM results in Table F-27 for PGA-A shows evidence of site-to-site variation and some interaction between site and flux that affects resistance either positively or negatively by up to an order of magnitude. Nine of the demonstration sites do not differ from the base case when low residue flux is used.

Table F-28 in Appendix F shows a flux effect of approximately 2.05 orders of magnitude as determined using GLM analyses surface finish, indicating there are no meaningful differences due to surface finishes. As was the case with the 10-mil pads, the differences from the base case for both GLMs essentially disappear after exposure to the 85/85 test environment.

Boxplot Displays of Multiple Comparison Results. The p-values for the ANOVA given above show the only test indicating a significant difference in mean leakage for the PGA-A circuit was the pre-test (shown in Figure 4-21). Boxplot displays of the other leakage measurements for PGA-A are given in Appendix F. Figure 4-21 illustrates the impact of flux that was identified as significant in the GLM analyses. As was true with 10-mil pads, every case with water soluble flux is higher (better) than the corresponding low residue analog, although all test responses were above the acceptance criteria. In subsequent results, the differences due to flux disappear. As mentioned above, this change is likely due to a cleansing effect from the 85/85 test environment.

  Comparison to Acceptance Criterion. There were no anomalies for PGA-A at pre-test, post-85/85, post-TS, or post-MS.

Pin Grid Array-B

  Examination of the GLM results in Table F-27 for PGA-B shows a strong effect due to flux of approximately 2.77 orders of magnitude. Thirteen of the demonstration sites do not differ from the base case when low residue flux is used, and the other two only differ slightly. Table F-28 also shows a strong flux effect of approximately 2.71 orders of magnitude as determined in the GLM analyses surface finish, indicating there are no meaningful differences due to surface finishes. As was the case with the 10-mil pads and PGA-A, the differences from the base case for both GLMs essentially disappear after exposure to the 85/85 test environment.

  Boxplot Displays of Multiple Comparison Results. The p-values for the ANOVA given above show the only test indicates a significant difference in mean leakage for the PGA-B circuit at pre-test. Figure 4-22 illustrates the impact of flux that was identified as significant in the GLM analyses. As was true with 10-mil pads and PGA-A, every case with water soluble flux is higher (better) than the corresponding low residue analog, though all test responses were above the acceptance criteria. In boxplots for the other test times, the differences due to flux disappear. As mentioned above, this change is likely due to a cleansing effect from the 85/85 test environment. Boxplot displays of the other leakage measurements for PGA-B are given in Appendix F.

  Comparison to Acceptance Criterion. There were no anomalies for PGA-B at pre-test, post-85/85, post-TS, or at post-MS.

Gull Wing

  Examination of the GLM results in Table F-27 for the Gull Wing shows a moderate effect due to flux of approximately 0.81 orders of magnitude. There is evidence of modest site-to-site variation and some interaction between site and flux. Eleven of the demonstration sites do not differ from the base case when low residue flux is used, and the other two only differ slightly. Table F-28 shows a flux effect of approximately 1.09 orders of magnitude as determined in the GLM analyses by surface finish, indicating there are no meaningful differences due to surface finishes. As was the case with the 10-mil pads, PGA-A, and PGA-B, the differences from the base case for both GLMs essentially disappear after exposure to the 85/85 test environment.

Boxplot Displays of Multiple Comparison Results. The p-values for the ANOVA given above show only the test time, with a significant difference in mean leakage for the gull wing circuit at pre-test, as illustrated in Figure 4-23. Boxplot displays of the leakage measurements for the gull wing at the other test times are given in Appendix F. Figure 4-23 illustrates the impact of flux that was identified as significant in the GLM analyses. As was true with 10-mil pads, PGA-A, and PGA-B, every case with water soluble flux is higher that the corresponding low residue analog, though all test responses were abofe the acceptance criteria. At subsequent test times, the differences due to flux disappear. As mentioned above, this change is likely due to a cleansing effect from the 85/85 test environment.

Comparison to Acceptance Criterion. There was one slight anomaly for the Gull Wing following 85/85. This value was 7.27 compared to the acceptance criteria of 7.7, so it is not of concern. There were no anomalies at post-TS or post-MS.

4.1.13 Stranded Wires

Two stranded wires were hand-soldered on the PWA (responses 22 and 23 in Table 4-1). One wire was soldered into PTHs, and the other was soldered to two terminals. Pre-test measurements for the stranded wire circuits were subjected to GLM analyses, as were the deltas after 85/85, thermal shock, and mechanical shock. The results of the GLM analyses are given in Tables F-29 and F-30. The GLM analyses indicate that the experimental parameters do not influence the stranded wire voltage measurements.

Boxplot Displays of Multiple Comparison Results. As with other circuits, an ANOVA was used to determine if there was a significant difference in the mean leakage measurements for the two stranded wire measurements. The p-values for the respective f-statistics for these two sets of voltage measurements are given in the following summary (all p-values > 0.01 are shaded). Table 4-20 shows no significant differences in the means at any test time. Boxplot displays of the pre-test voltage measurements (mV) can be found in Appendix F.

Table 4-20. P-Values for Stranded Wire Test Results

Test Time	P-Value for 10-mil Pads	P-Value for PGA-A
Pre-test	0.951	0.203
Post-85/85	0.410	0.407
Post-TS	0.537	0.440
Post-MS	0.396	0.408

MS = mechanical shock; PGA = pin grid array; TS = thermal shock.

Comparison to Acceptance Criterion. The acceptance criteria requires changes in voltage to be within 0.356V of their pre-test measurements. There were no anomalies for either Stranded Wire 1 or 2 at pre-test or following 85/85. There was one minor anomaly at post-TS for SW2 where the measured increase in voltage was 0.371V, compared to the upper acceptable limit of 0.356V. At post-MS, there was one minor anomaly for SW1 (0.375) and four minor anomalies for SW2 (0.359, 0.37O, 0.365, and 0.357). All of these anomalies were right at the upper limit and are not of concern.

4.1.14 Failure Analysis

Following the analysis of the test boards, ion chromatography was used as a tool to analyze boards that failed 85°C/85% relative humidity exposure. Contamination Studies Laboratories, Inc. (CSL) in Kokomo, Indiana, conducted this failure analysis. The purpose of the analysis was to determine if any links exist between board contamination from fabrication and assembly process residues and the electrical anomalies.

<u>**Test Sample Identification**</u>

Twenty boards were selected for the ion chromatography analysis including: 1) a test group of boards that failed after exposure to 85°C/85% relative humidity; and 2) a control group of boards that were not subjected to the 85°C/85% relative humidity environment. The test group consisted of 10 boards (identified in Table F-1) that exhibited various anomalies following 85°C/85% relative humidity testing. For the control group, the 10 boards selected represented each of the six surface finishes and a variety of assembly processes and sites. Table 4-21 summarizes the 20 boards selected for ion chromatography analysis.

<u>**Visual Observations**</u>

The test group of boards was visually inspected to identify any obvious anomalies or defects. All 10 boards exhibited visual anomalies in varying degrees. The most common anomalies were solder cracking and discoloration of the surface metalization. Less common were pinholes and foreign material (e.g., solder balls). The following photographs show examples of the more prominent visual defects.

Visual Observations of Anomalies on Select Test Boards

A.

B.

C.

D.

E.

F.

G.

H.
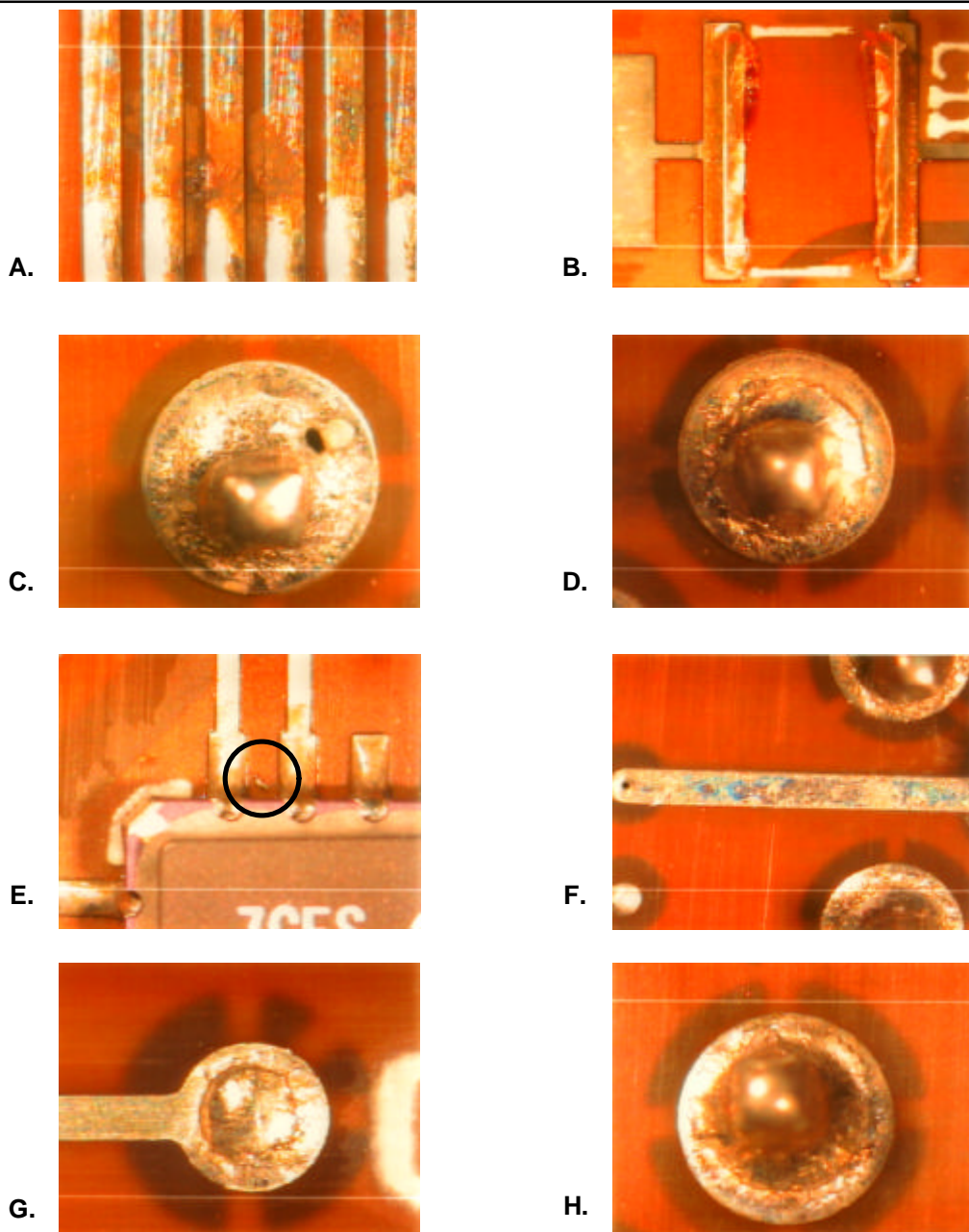
A.   Burnt etches near U102 on Board #082-2
B.   Excessive WS paste residues beneath SMT component on Board #030-4
C.   Pin hole in feed through on Board #056-4
D.   Solder crack around perimeter of J5 connector feed through on Board #056-4
E.   Solder ball between pins of U3 on Board #013-1
F.   Discoloration on trace connected to J6 on Board #015-4
G.   Solder crack around perimeter of filled via near C16 on Board #102-4
H.   Solder crack around perimeter of J9 connector feed through Board #086-2

Table 4-21. Identification of Assemblies Selected for Ion Chromatography Analysis

Finish	Board #	Assembly Process	Site
Untested Board (Control Group)			
HASL	077-4	LR	1
HASL	096-2	WS	2
Nickel/Gold	068-4	WS	7
Nickel/Gold	017-4	LR	12
Nickel/Palladium/Gold	001-4	LR	15
OSP	061-2	WS	3
Immersion Silver	085-4	WS	8
Immersion Silver	074-3	LR	9
Immersion Tin	103-4	WS	4
Immersion Tin	034-4	LR	10
Post-85/85 Exposure (Anomaly Group)			
HASL	083-2	WS	1
Nickel/Gold	013-1	LR	13
Nickel/Gold	015-4	LR	14
OSP	056-4	LR	5
Immersion Silver	082-2	LR	11
Immersion Silver	094-4	WS	12
Immersion Tin	030-4	WS	9
Immersion Tin	032-4	LR	8
Immersion Tin	086-2	WS	7
Immersion Tin	102-4	WS	10

LR = low residue flux; WS = water soluble flux.

Test Method

The fundamental steps for conducting ion chromatography analysis per IPC-TM-650, method 2.3.28 are as follows:

1. The lab technician (LT) placed the test board(s) into clean KAPAK™ (heat-sealable polyester film) bag(s).
2. The LT introduced a mixture of isopropanol (75 percent volume) and deionized water (25 percent volume) into the bag(s), immersing the test board(s). NOTE: The heat-sealed bag(s) included an opening for ventilation.
3. The LT inserted the bag(s) into an 80 °C water bath for one hour.
4. The LT removed the bag(s) from the water bath.
5. The LT separated the test board(s) from the bags.
6. The LT placed the test board(s) on a clean holding rack for air drying at room temperature.
7. The LT performed controls and blanks on the Dionex ion chromatography system before the test began. NOTE: NIST-traceable standards for system calibration were used.
8. The LT injected a 1.5 ml sample of each test sample's extract solution using a 5 mM sodium bicarbonate eluent.

Failure Analysis Results

The following tables show the ion chromatography data for each surface finish analyzed, reported as micrograms of the residue species per square inch of extracted surface (μg/in^2). NOTE: This measure should not be confused with micrograms of sodium chloride equivalent per square inch, which is the common measure for most ionic cleanliness test instruments.

Table 4-22. Ion Chromatography Anion $^{(-)}$ Data (HASL) [a]

Sample Description	Assembly Process	Site	Ion Chromatography Data		
			Cl$^-$	Br$^-$	WOA
Untested Boards (Control Group)					
Board #077-4	LR	1	5.87	3.82	154.33
Board #096-2	WS	2	14.53	10.01	3.01
Tested Boards (Anomaly Group)					
Board #083-2	WS	1	5.36	2.73	7.15

[a] Test results reported as micrograms of the residue species per square inch of extracted surface (μg/in^2).
Br$^-$ = bromide ion; Cl$^-$ = chloride ion; LR = low residue flux; WOA = weak organic acids; WS = water soluble flux.

Table 4-23. Ion Chromatography Anion $^{(-)}$ Data (Immersion Tin) [a]

Sample Description	Assembly Process	Site	Ion Chromatography Data		
			Cl$^-$	Br$^-$	WOA
Untested Boards (Control Group)					
Board #034-4	LR	10	0.87	5.26	140.45
Board #103-4	WS	4	5.10	2.98	3.30
Tested Boards (Anomaly Group)					
Board #032-4	LR	8	1.75	4.12	15.78
Board # 030-4	WS	9	1.70	5.68	15.46
Board #086-2	WS	7	2.99	3.30	9.23
Board #102-4	WS	10	2.33	3.16	4.63

[a] Test results reported as micrograms of the residue species per square inch of extracted surface (μg/in^2).
Br$^-$ = bromide ion; Cl$^-$ = chloride ion; LR = low residue flux; WOA = weak organic acids; WS = water soluble flux.

Table 4-24. Ion Chromatography Anion $^{(-)}$ Data (Immersion Silver) [a]

Sample Description	Assembly Process	Site	Ion Chromatography Data		
			Cl $^-$	Br $^-$	WOA
Untested Boards (Control Group)					
Board #074-3	LR	9	0.60	6.53	159.48
Board #085-4	WS	8	4.77	2.64	5.22
Tested Boards (Anomaly Group)					
Board #082-2	LR	11	2.59	3.25	4.28
Board #094-4	WS	12	2.53	4.65	5.78

[a] Test results reported as micrograms of the residue species per square inch of extracted surface (μg/in^2).

Br $^-$ = bromide ion; Cl $^-$ = chloride ion; LR = low residue flux; WOA = weak organic acids; WS = water soluble flux.

Table 4-25. Ion Chromatography Anion $^{(-)}$ Data (Nickel/Gold) [a]

Sample Description	Assembly Process	Site	Ion Chromatography Data		
			Cl $^-$	Br $^-$	WOA
Untested Boards (Control Group)					
Board #017-4	LR	12	1.01	5.34	150.81
Board #068-4	WS	7	4.57	1.78	3.08
Tested Boards (Anomaly Group)					
Board #013-1	LR	13	2.44	3.56	15.13
Board #015-4	LR	14	1.63	2.80	14.04

[a] Test results reported as micrograms of the residue species per square inch of extracted surface (μg/in^2).

Br $^-$ = bromide ion; Cl $^-$ = chloride ion; LR = low residue flux; WOA = weak organic acids; WS = water soluble flux.

Table 4-26. Ion Chromatography Anion $^{(-)}$ Data (OSP) [a]

Sample Description	Assembly Process	Site	Ion Chromatography Data		
			Cl $^-$	Br $^-$	WOA
Untested Boards (Control Group)					
Board #061-2	WS	3	3.57	3.45	2.57
Tested Boards (Anomaly Group)					
Board #056-4	LR	5	2.40	4.28	26.41

[a] Test results reported as micrograms of the residue species per square inch of extracted surface (μg/in^2).

Br $^-$ = bromide ion; Cl $^-$ = chloride ion; LR = low residue flux; WOA = weak organic acids; WS = water soluble flux.

Table 4-27. Ion Chromatography Anion $^{(-)}$ Data (Nickel/Palladium/Gold) ^{a}

Sample Description	Assembly Process	Site	Ion Chromatography Data		
			Cl $^{-}$	Br $^{-}$	WOA
Untested Boards (Control Group)					
Board #001-4	LR	15	0.84	5.15	151.18

^{a} Test results reported as micrograms of the residue species per square inch of extracted surface (μg/in^{2}).
Br $^{-}$ = bromide ion; Cl $^{-}$ = chloride ion; LR = low residue flux; WOA = weak organic acids.

Chloride. Chloride ion (Cl $^{-}$) is one of the more detrimental materials found on printed circuit assemblies. Chloride, which can come from a variety of sources, is most often attributable to flux residues. Chloride will generally initiate and propagate electrochemical failure mechanisms, such as metal migration and electrolytic corrosion, when combined with water vapor and an electrical potential. The tolerance for chloride on an assembly depends on the flux chemistry that an assembler uses. An assembly processed with high-solids rosin fluxes (RA or RMA) can tolerate higher levels of chloride due to the encapsulating nature of the rosin. water soluble fluxes and no-clean fluxes, which flux manufacturers typically formulate using resins or very low levels of rosin, do not have this encapsulating protection. Therefore, they require lower levels of flux on final assemblies.

CSL recommends a maximum chloride level of no more than 4.5 to 5.0 μg/in^{2} for finished assemblies processed with water-soluble fluxes, and no more than 2.5 μg/in^{2} for finished assemblies processed with low solids (no-clean) fluxes. Although these recommended maximums do not presently appear in any nationally-accepted specifications or standards, years of failure analysis experience dealing with CSL's numerous customers serves as a basis or starting point.

With the exception of the HASL boards, all untested and tested assemblies exhibit levels at or below CSL's recommended guidelines. Therefore, the observed chloride levels are not considered to be detrimental from an electrochemical standpoint.

The two untested (control) boards with the HASL finish exhibit levels significantly above CSL's recommended limits and are therefore at risk for electrochemical failures. For the board processed with low residue (no clean) flux, CSL suspects that the high chloride is due mainly to the board fabricator's use of a chloride-activated HASL flux coupled with an ineffective post-HASL cleaning process. For the board processed with water-soluble flux, high chloride may be the result of both HASL residues and water soluble flux residues. In both cases, ineffective cleaning is the likely culprit.

The one tested HASL board with the reported anomaly exhibits a level only slightly above CSL's recommended limit. Although the chloride in the observed amount places the assembly at slight risk for electrochemical failures, CSL does not believe in this case that chloride contamination is the root cause for reported open PTH failures on Board #083-2.

Based on the fact the tested boards with known anomalies exhibit levels near or below CSL's recommended guidelines, there is reasonable confidence that the anomalies identified in the performance testing are not the result of chloride residues. The majority of the anomalies are either mechanical in nature (e.g., poor solder joint integrity) or component non-conformities (e.g., wrong value and device failures).

Bromide. Bromide ion (Br⁻) is generally attributable to the bromide fire retardant added to epoxy-glass laminates to give fire resistance, and which is subsequently extracted in the ion chromatography analytical procedure. Bromide can also sometimes come from solder masks, marking inks, or fluxes that have a bromide activator material. Bromide, when from the fire retardant, is not a material that typically degrades the long-term reliability of electronic assemblies. If bromide comes from a flux residue, it can be corrosive, as other halides can be. The level of bromide varies depending on the porosity of the laminate and/or mask, the degree of over/under cure of the laminate or mask, or the number of exposures to reflow temperatures.

For epoxy-glass laminate, bromide levels typically fall within the range of 0 to 7 μg/in^2, depending upon the amount of fire retardant the laminate manufacturer has added. Exposure to reflow conditions tends to increase the porosity of the laminate and mask. With several exposures to reflow conditions, bromide can reach levels as high as 10 to 12 μg/in^2. The testing laboratory, CSL, does not presently consider bromide levels under 12 μg/in^2 to be detrimental on organic PWBs. However, CSL considers levels between 12 μg/in^2 to 20 μg/in^2 to be a borderline risk for failures if attributable to corrosive flux residues. Furthermore, levels above 20 μg/in^2 are considered to be a significant threat for failures if attributable to corrosive flux residues.

Based on CSL's guidelines, the bromide levels on the assemblies are acceptably low and as such do not pose a threat for electrochemical failures. CSL attributes these bromide levels to the fire retardant material in the FR-4 laminate.

Weak Organic Acids. Weak organic acids (WOAs), such as adipic or succinic acid, serve as activator compounds in many fluxes, especially no-clean fluxes. WOAs are typically benign materials and are therefore not a threat to long term reliability. In order to avoid formulation disclosure difficulties with flux manufacturers, all detected WOA species were grouped together and referred to collectively as WOAs.

WOA levels vary greatly, depending on the delivery method (e.g., foam vs. spray) and the preheat dynamics. In general, water-soluble fluxes have a much lower WOA content than do low-solids (no clean) fluxes, and the amount of residual WOA is proportional to the amount of residual flux. Bare boards typically do not contain WOA residues.

Table 4-28. Acceptance Levels for Weak Organic Acids

Process	Level
Spray-applied, low solids solder paste deposition	0 - 20 μg/in^2
Foam-applied flux process w/air knife	20 - 120 μg/in^2
Spray-applied, low solids flux	250 - 400 μg/in^2

When WOA levels are under 400 μg/in^2, the residues are generally not detrimental. Excessive WOA amounts (appreciably greater than 400 μg/in^2) present a significant reliability threat for finished assemblies. Low levels of WOA can also create electrical performance problems in certain applications.

- An excessive amount of flux can produce the situation in which the thermal energy of preheat is spent driving off the solvent, therefore not allowing the flux to reach its full activation temperature. Unreacted flux residues readily absorb moisture that promotes the formation of corrosion and the potential for current leakage failures.

- Fully reacted and therefore benign WOAs act as insulators that, even at levels as low as 10 μg/in^2, can potentially create a high resistance contact-to-contact resistance problem on devices such as switches.

The observed levels of WOAs on all 20 boards are typical and therefore are not detrimental from an electrochemical standpoint. As expected, more WOA is evident on the boards processed with low residue fluxes than on those processed with water soluble fluxes.

4.1.15 Summary and Conclusions

The test PWA provides electrical responses for 23 individual circuits that fall into the following seven major circuit groups:

- high current low voltage (HCLV);
- high voltage low current (HVLC);
- high speed digital (HSD);
- high frequency low pass filter (HF LPF);
- high frequency transmission line coupler (HF TLC);
- leakage networks; and
- stranded wire (SW).

The first four circuit groups have both PTH and SMT components.

These characteristics make the test PWA an excellent discriminating test vehicle to discover problem areas associated with new circuit card technologies, materials, and processes. Exposure to environmental conditions such as the 85/85, thermal shock, and mechanical shock used in this test program can accelerate the discovery process. Table 4-29 illustrates how problem areas developed during the three tests.

Table 4-29 clearly identifies the HF LPF circuits as a problem area. The main problem was related to open PTHs, which were discussed previously in Section 4.1.10. The HF LPF anomalies resulted from a combination of board fabrication materials and processes and board design (i.e., the small diameter vias in the HF LPF circuit). Product designers should be aware of these phenomena when considering a change to the new surface finishes.

Table 4-29. Frequency of Anomalies by Individual Circuit Over Test Times

	Circuitry	Post-85/85	Post-Thermal shock	Post-Mechanical Shock	Comments
HCLV					
1	HCLV PTH	0	0	12	Some should be subjected to failure analysis.
2	HCLV SMT	0	0	158	SMT components came off board during mechanical shock.
HVLC					
3	HVLC PTH	0	0	0	Excellent performance throughout.
4	HVLC SMT	1	1	164	SMT components came off board during mechanical shock.
HSD					
5	HSD PTH	0	2	2	Component problem.
6	HSD SMT	1	2	1	Component problem.
HF LPF					
7	HF PTH 50MHz	4	15	15	Perform failure analysis related to open PTH (see Section 4.1.10).
8	HF PTH f(-3dB)	4	15	18	Perform failure analysis related to open PTH (see Section 4.1.10).
9	HF PTH f(-40dB)	4	13	14	Perform failure analysis related to open PTH (see Section 4.1.10).
10	HF SMT 50MHz	0	18	30	Perform failure analysis related to open PTH (see Section 4.1.10).
11	HF SMT f(-3dB)	0	16	29	Perform failure analysis related to open PTH (see Section 4.1.10).
12	HF SMT f(-40dB)	1	27	65	Perform failure analysis related to open PTH (see Section 4.1.10).
HFTLC					
13	HF TLC 50MHz	0	0	7	Minor anomalies.
14	HF TLC 500MHz	0	0	1	Minor anomalies.
15	HF TLC 1GHz	0	1	1	Minor anomalies.
16	HF TLC RNF				
17	HF TLC RNR	1	2	5	Minor anomalies.
Leakage					
18	10-mil Pads	0	0	0	Excellent performance throughout.
19	PGA-A	0	0	0	Excellent performance throughout.
20	PGA-B	0	0	0	Excellent performance throughout.
21	Gull Wing	1	0	0	Excellent performance throughout.
Stranded Wire					
22	SW 1	0	0	1	Excellent performance throughout.
23	SW 2	0	1	4	Minor anomalies.

HCLV = high current low voltage; HF = high frequency; HSD = high speed digital; HVLC = high voltage low current;
PGA = pin grid array; PTH = plated through hole; SMT = surface mount technology; SW = stranded wire;
TLC = transmission line coupler.

With the exception of the HCLV SMT and HVLC SMT circuits in the mechanical shock test, the surface finishes under study were very robust to the environmental exposures. When assessing the HCLV SMT and HVLC SMT results, product and process designers should consider the severity of the mechanical shock test (25 drops, five times on each edge excluding the connector edge and five times on each face, to a concrete surface from a height of one meter). Also, HCLV SMT and HVLC SMT anomalies due to SMT components coming off the board during the execution of the mechanical shock test were equally distributed across all surface finishes including the HASL baseline.

Based on the results of the Failure Analysis:

- Observed levels of bromide and WOA on all 20 assemblies are typical and therefore not detrimental from an electrochemical standpoint.
- Based on the fact the tested boards with known anomalies exhibit levels near or below CSL's recommended guidelines, there is reasonable confidence that the anomalies are not the result of chloride, bromide, or WOA contamination.
- From an overall contamination standpoint, the five non-HASL surface finishes tested in this analysis performed as well if not better against the HASL finish.
- Solder joint cracking failures were greater with the HASL finish than with the alternative finishes. The opens occurred along the interface of the component leads on these older PTH technology boards.

4.1.16 Boxplot Displays

Boxplot displays are presented here for selected results as discussed in this Chapter. Boxplots of the remaining test results are presented in Appendix F.
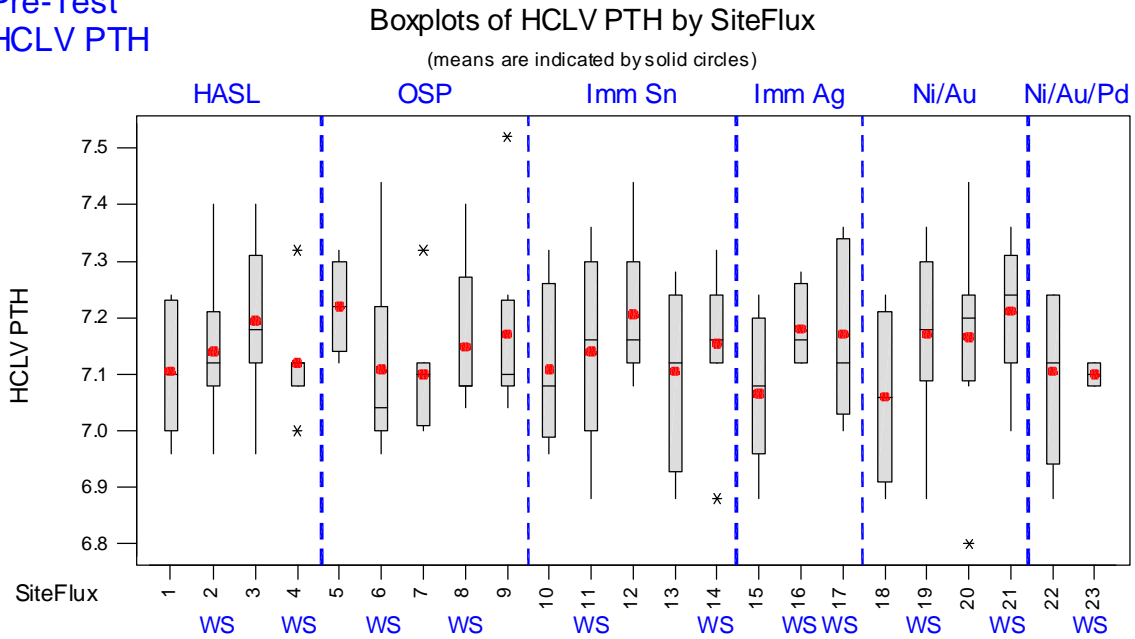
Figure 4-1. Boxplot Displays for HCLV PTH Measurements (volts) at Pre-test by Surface Finish
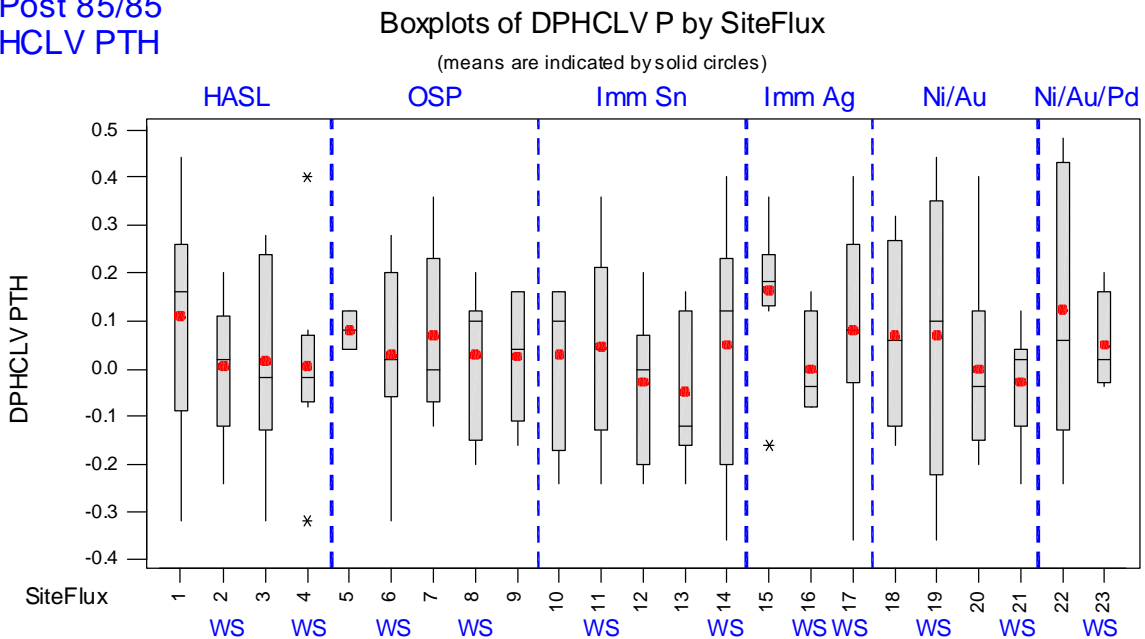
Figure 4-2. Boxplot Displays for HCLV PTH Post 85/85 – Pre-test Measurements (volts) by Surface Finish
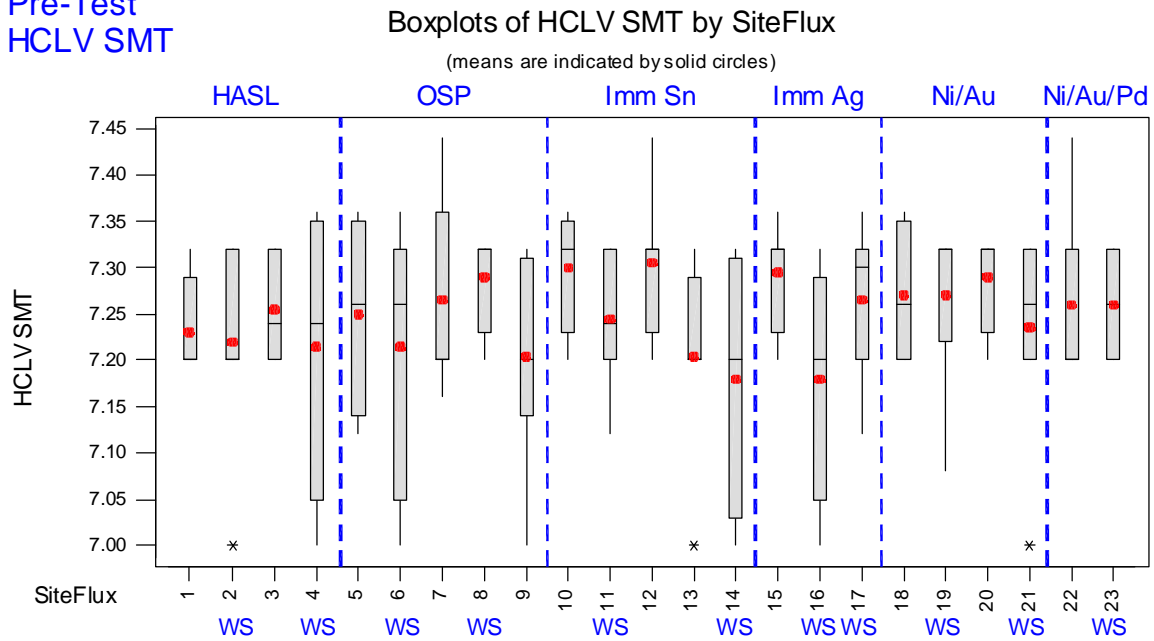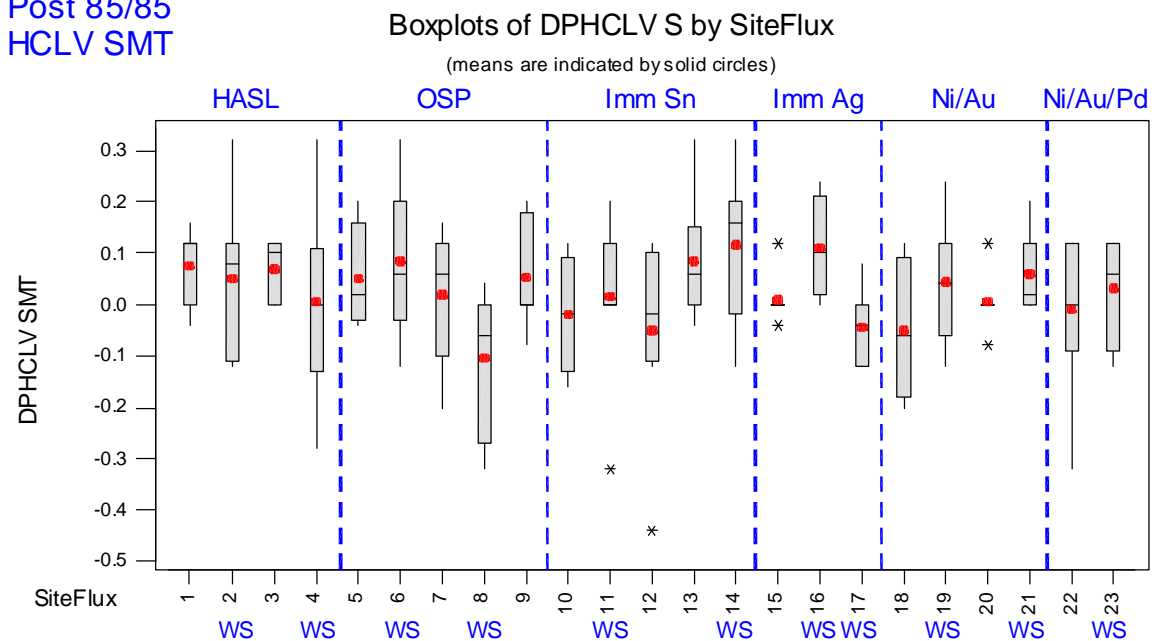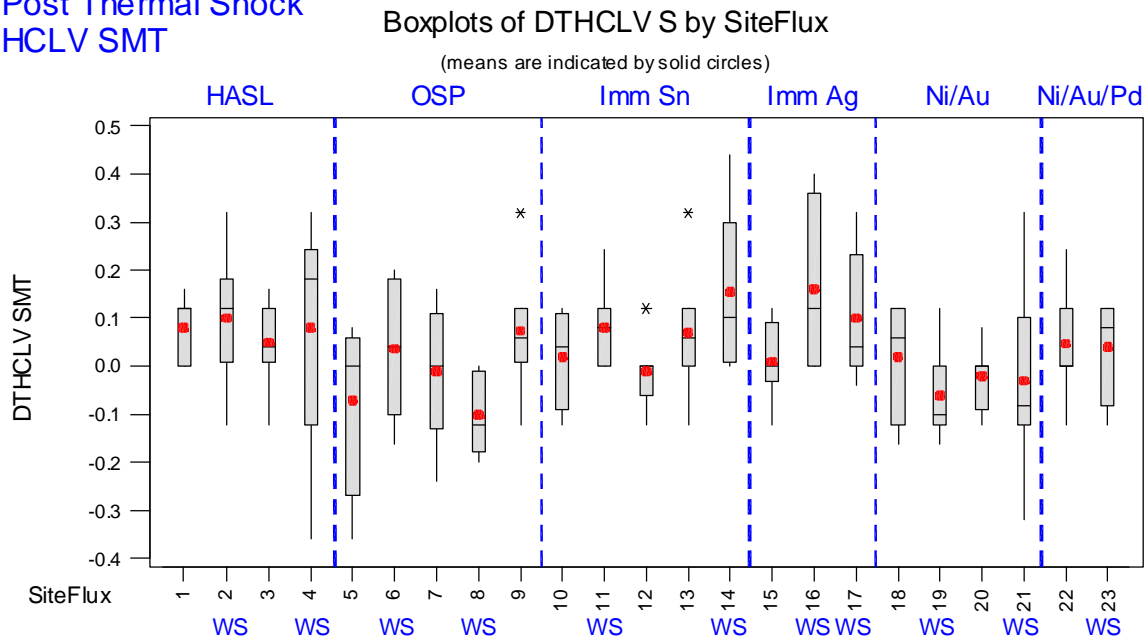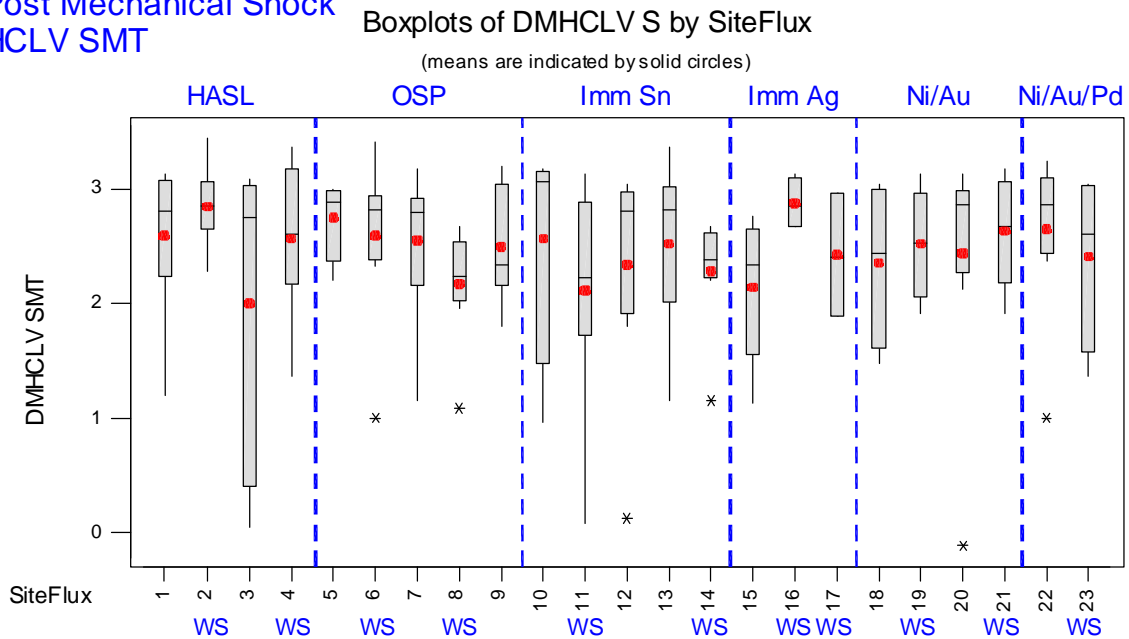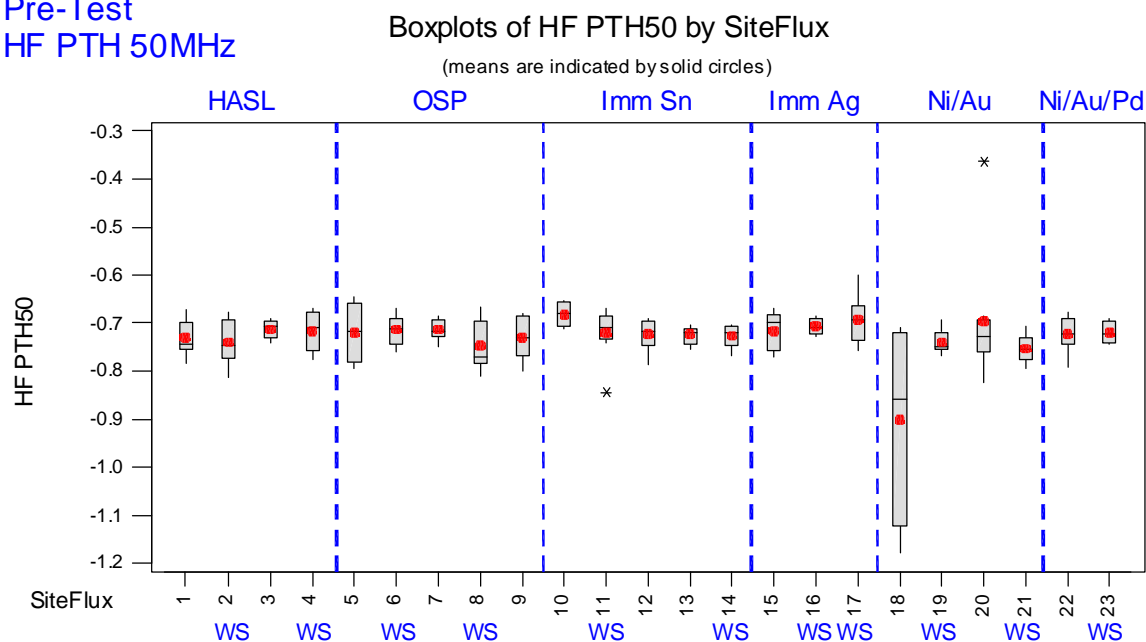(Acceptance Criterion = $\Delta<0.5V$)

Post Thermal Shock HCLV PTH

Boxplots of DTHCLV P by SiteFlux

(means are indicated by solid circles)
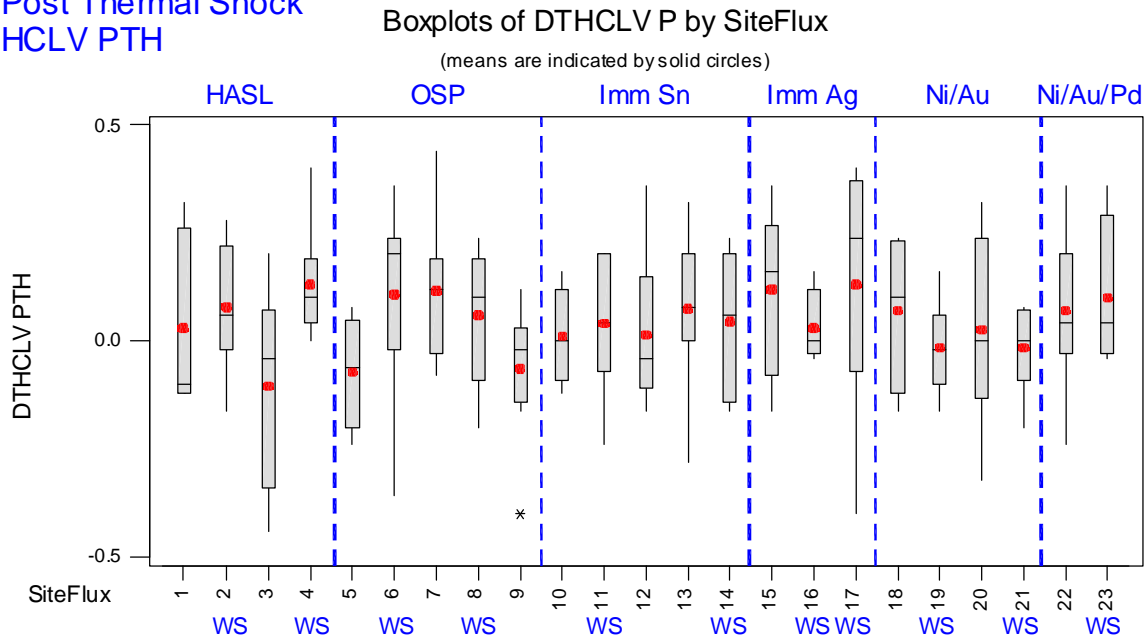
Figure 4-3. Boxplot Displays for HCLV PTH Post TS - Pre-Test Measurements (volts) by Surface Finish
(Acceptance Criterion = Δ<0.5V)

Post Mechanical Shock HCLV PTH

Boxplots of DMHCLV P by SiteFlux

(means are indicated by solid circles)
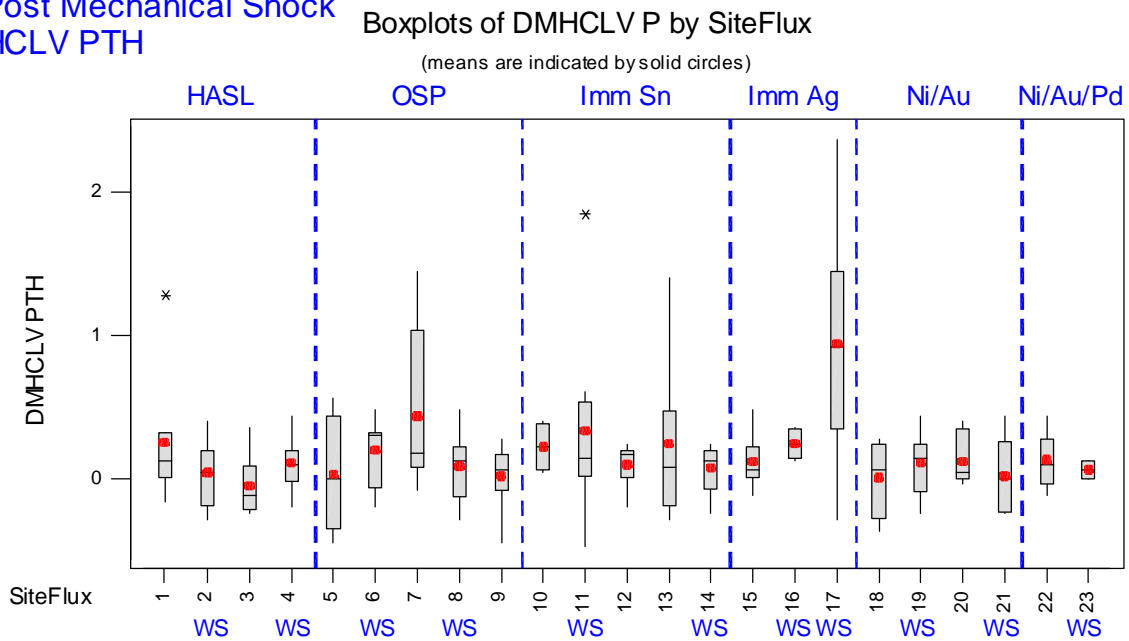
Figure 4-4. Boxplot Displays for HCLV PTH Post MS - Pre-Test Measurements (volts) by Surface Finish
(Acceptance Criterion = Δ<0.5V)

Figure 4-5. Boxplot Displays for HCLV SMT Measurements (volts) at Pre-Test by Surface Finish

Figure 4-6. Boxplot Displays for HCLV PTH Post 85/85 - Pre-Test Measurements (volts) by Surface Finish
(Acceptance Criterion = Δ<0.5V)

Figure 4-7. Boxplot Displays for HCLV PTH Post TS - Pre-Test Measurements (volts) by Surface Finish

(Acceptance Criterion = Δ<0.5V)

Figure 4-8. Boxplot Displays for HCLV PTH Post MS - Pre-Test Measurements (volts) by Surface Finish

(Acceptance Criterion = Δ<0.5V)

Figure 4-9. Boxplot Displays for HF PTH 50MHz Measurements at Pre-Test (dB) by Surface Finish
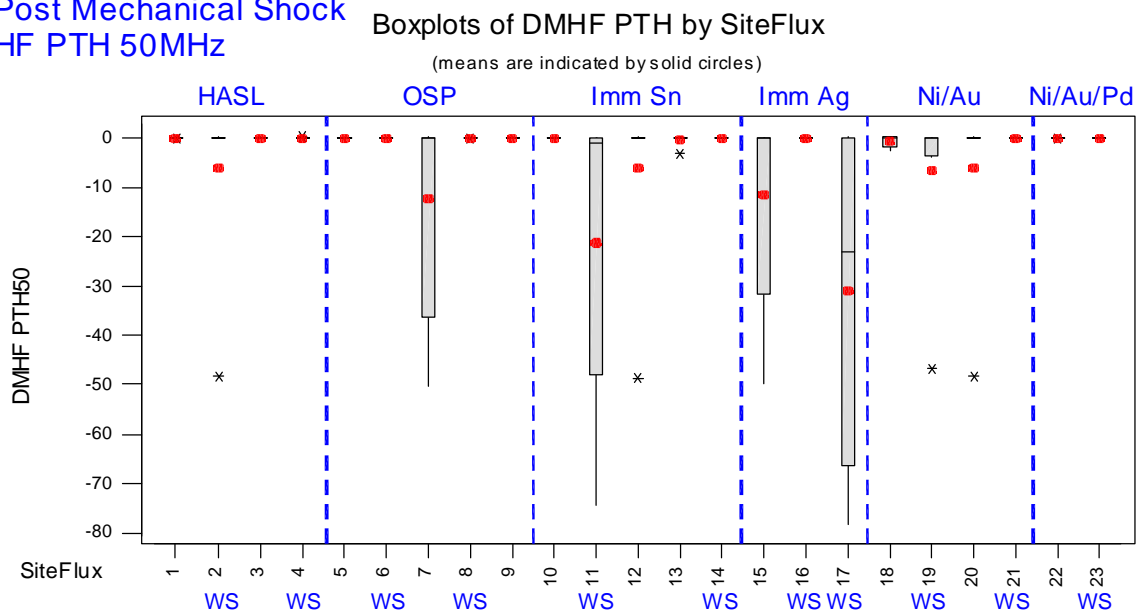
Figure 4-10. Boxplot Displays for HF PTH 50MHz Post MS - Pre-Test Measurements (dB) by Surface Finish
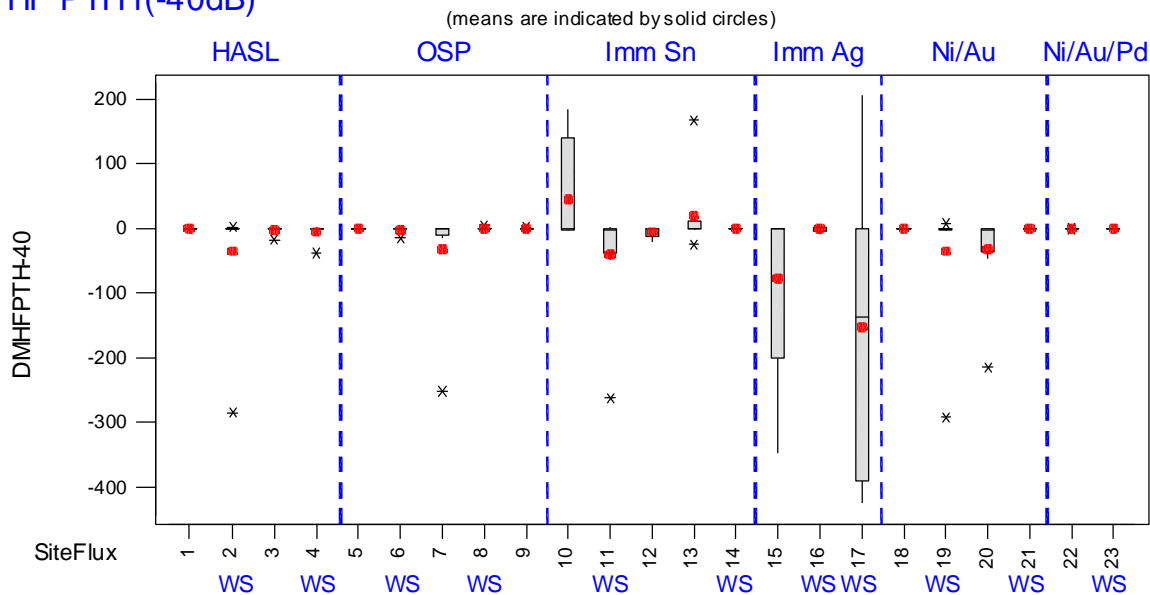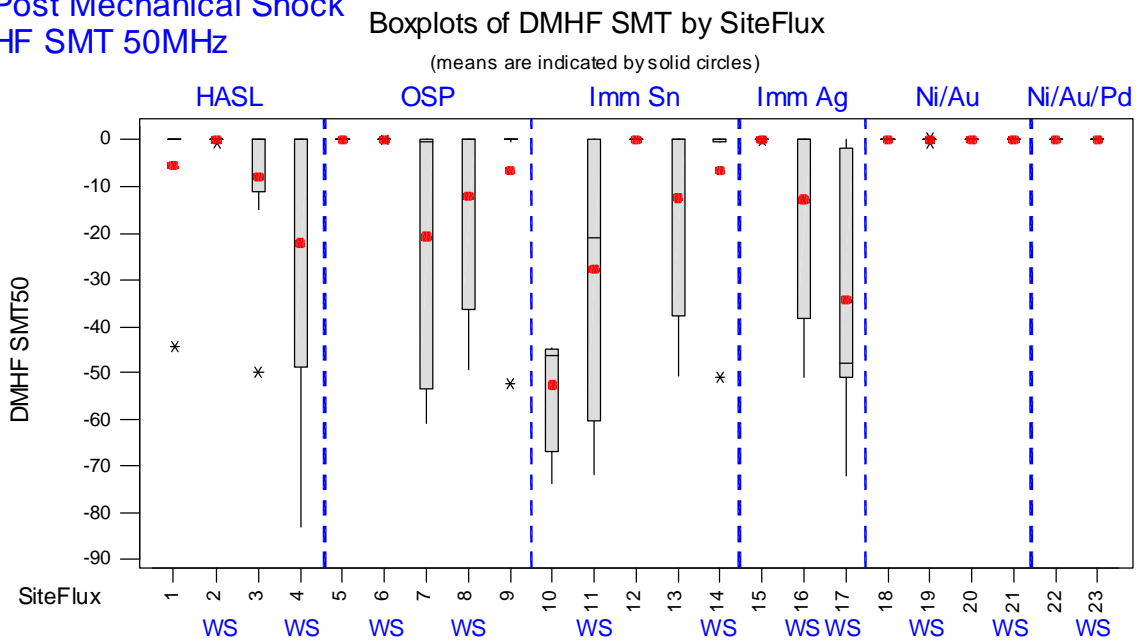(Acceptance Criterion = ±5dB of Pre-test)
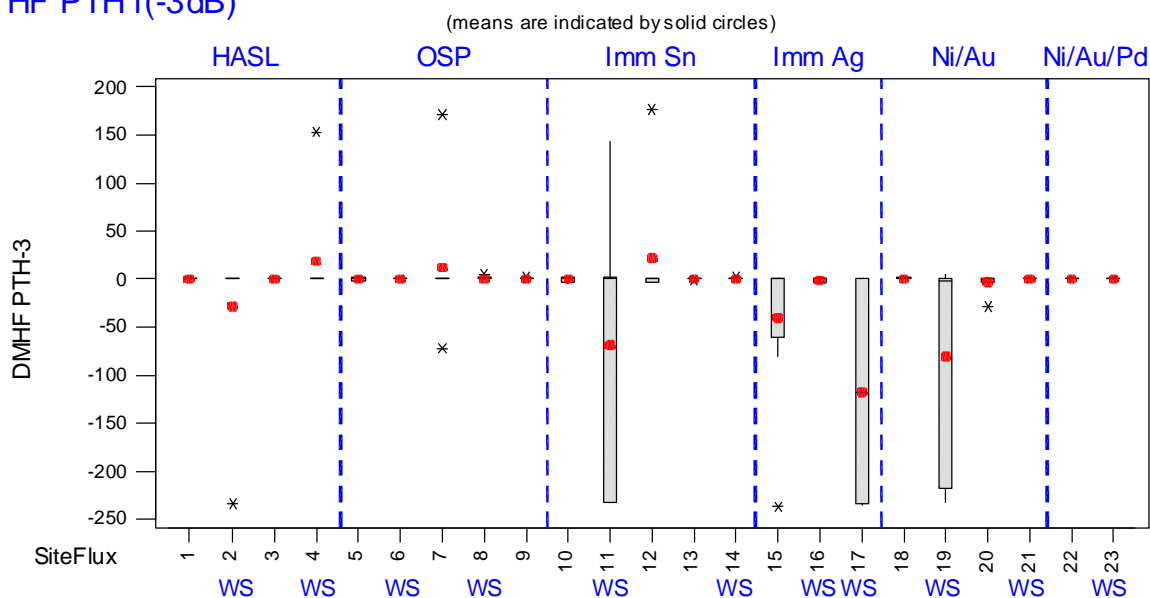
Figure 4-11. Boxplot Displays for HF PTH f(-3dB) Post MS - Pre-Test Measurements (MHz) by Surface Finish

(Acceptance Criterion = ±50MHz of Pre-test)

Figure 4-12. Boxplot Displays for HF PTH f(-40dB) Post MS - Pre-Test Measurements (MHz) by Surf. Finish

(Acceptance Criterion = ±50MHz of Pre-test)

Figure 4-13. Boxplot Displays for HF SMT 50MHz Post MS - Pre-Test Measurements (dB) by Surface Finish

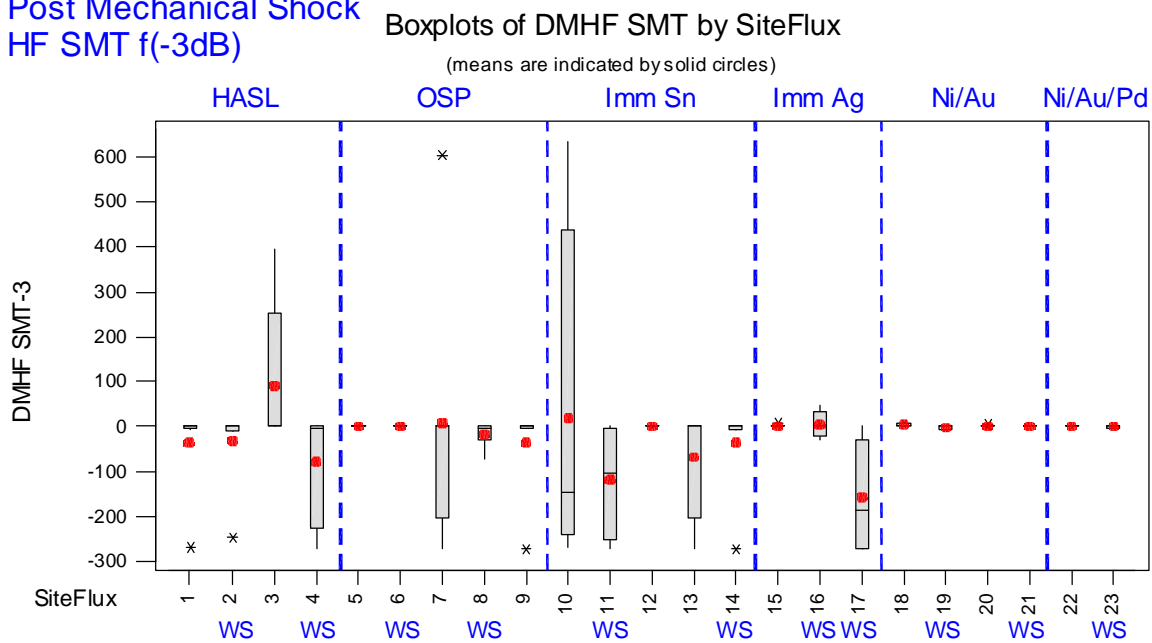(Acceptance Criterion = ±5dB of Pre-test)

Figure 4-14. Boxplot Displays for HF SMT f(-3dB) Post MS - Pre-Test Measurements (MHz) by Surf. Finish

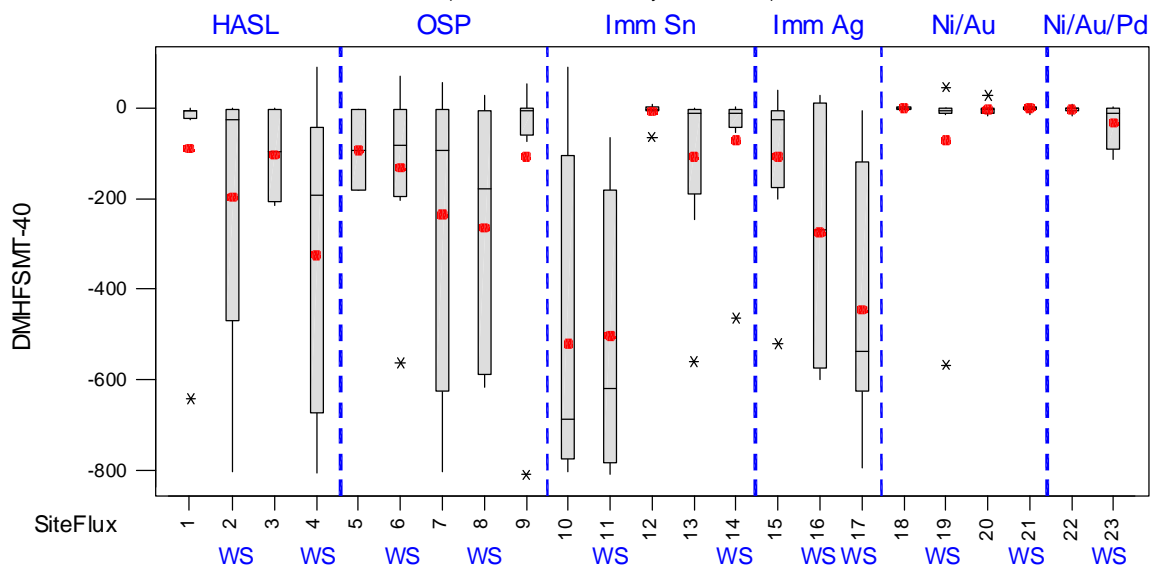(Acceptance Criterion = ±50MHz of Pre-test)

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Figure 4-15. Boxplot Displays for HF SMT f(-40dB) Post MS - Pre-Test Measurements (MHz) by Surface Finish

(Acceptance Criterion = ±50MHz of Pre-test)

Figure 4-16. Boxplot Displays for HF TLC 50MHz Post MS - Pre-Test Measurements (dB) by Surface Finish

(Acceptance Criterion = ±5dB of Pre-test)

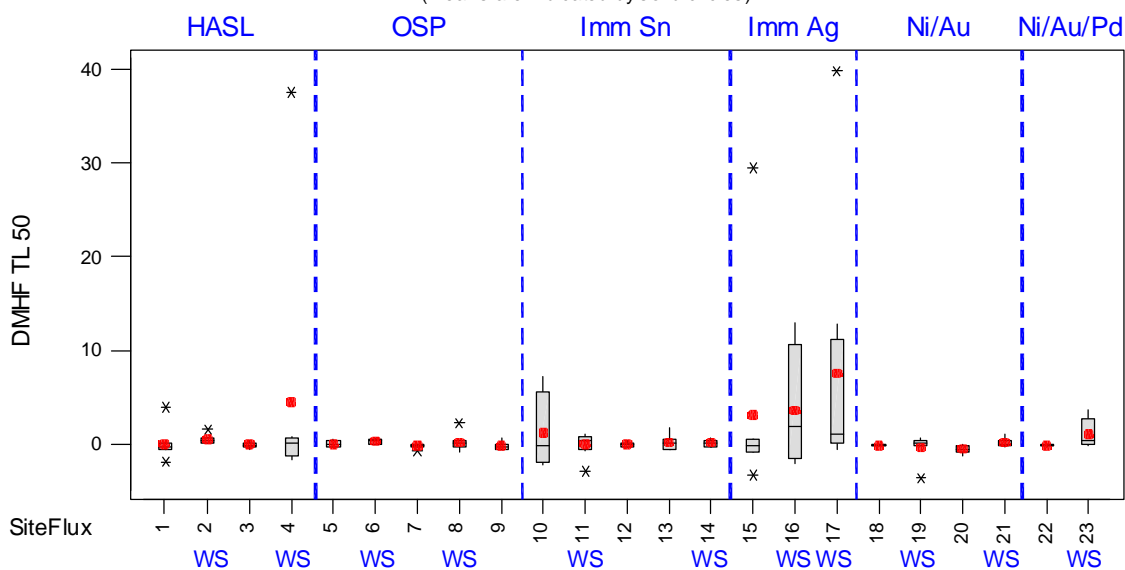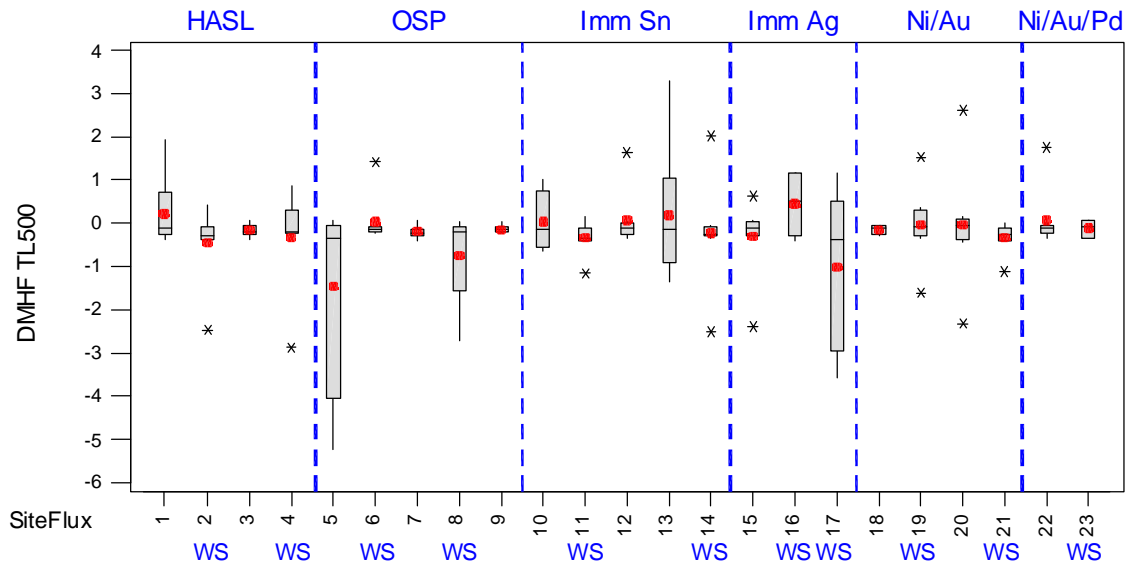**Figure 4-17. Boxplot Displays for HF TLC 500MHz Post MS - Pre-Test Measurements (dB) by Surface Finish**
(Acceptance Criterion = ±5dB of Pre-test)
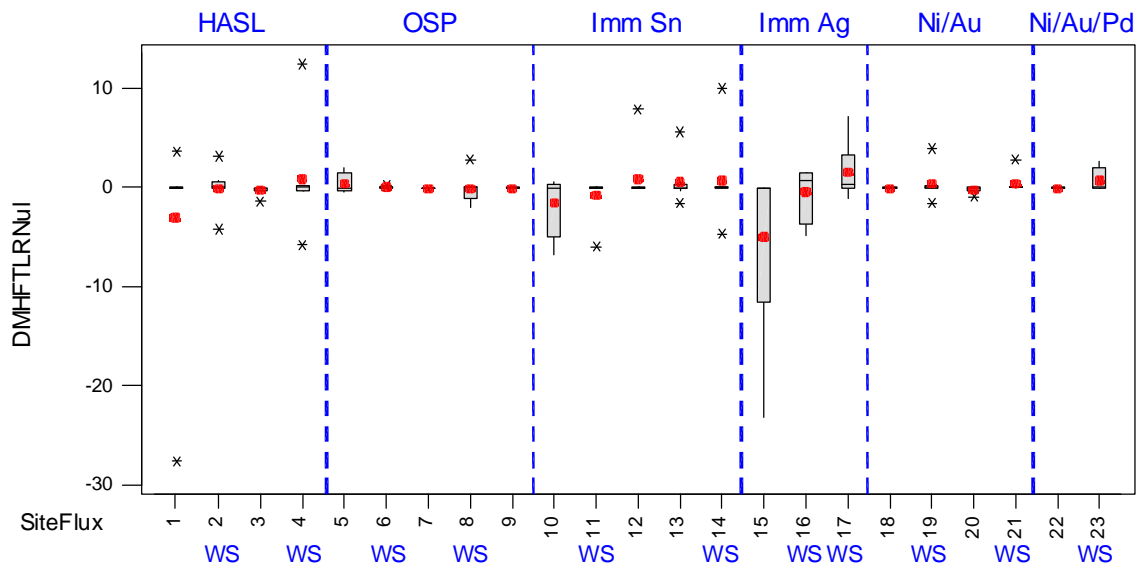
Figure 4-18. Boxplot Displays for HF TLC RNR Post MS - Pre-Test Measurements (dB) by Surface Finish
(Acceptance Criterion = <10dB increase over Pre-test)
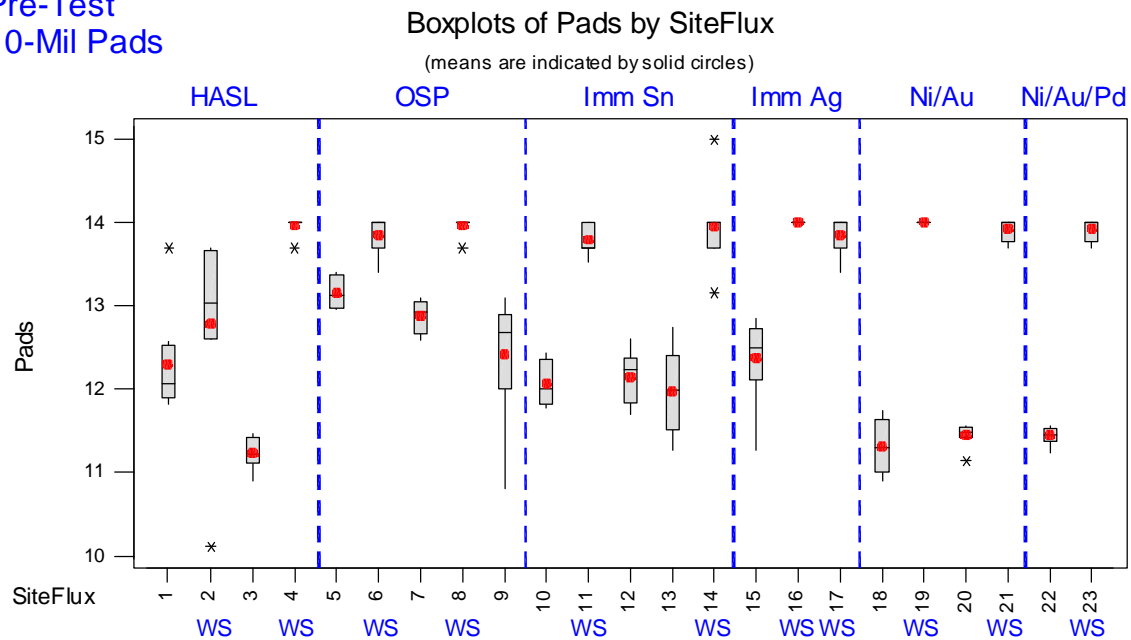
Figure 4-19. Boxplot Displays for 10-Mil Pad Measurements ($\log_{10}$ ohms) at Pre-Test by Surface Finish
(Acceptance Criterion = Resistance > 7.7 $\log_{10}$ ohms)
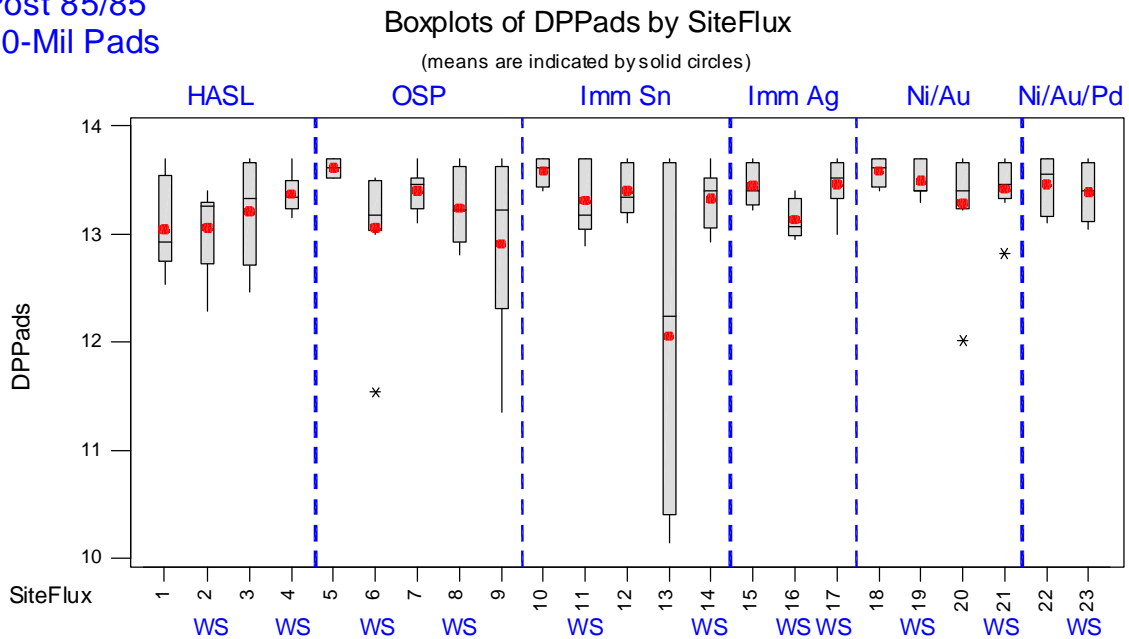
Figure 4-20. Boxplot Displays for 10-Mil Pad Post 85/85 - Pre-Test Measurements ($\log_{10}$ ohms) by Surface Finish
(Acceptance Criterion = Resistance > 7.7 $\log_{10}$ ohms)
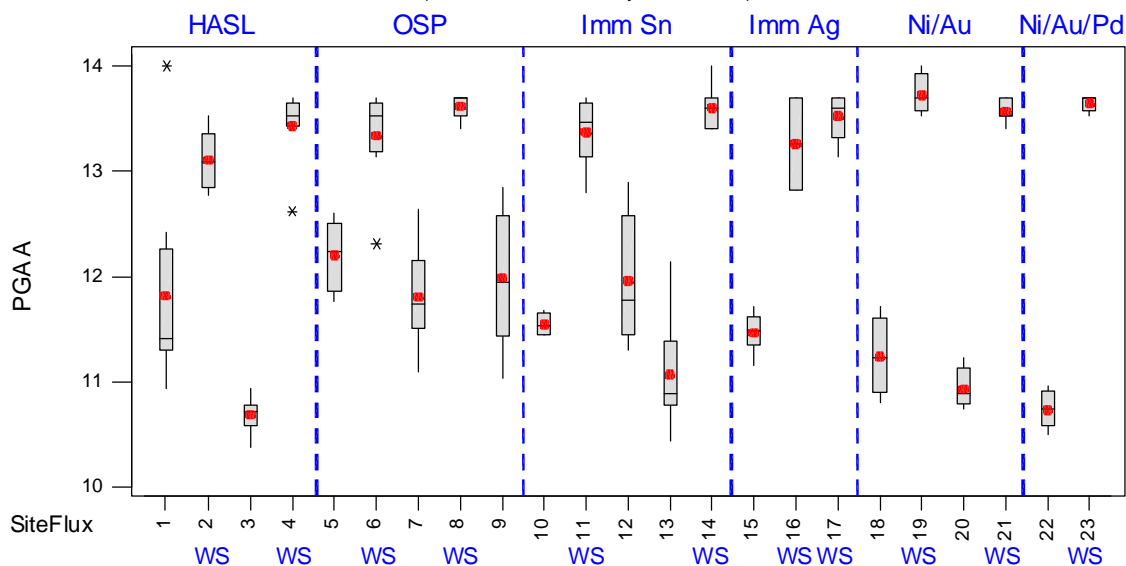
Figure 4-21. Boxplot Displays for PGA-A Measurements (log_{10} ohms) at Pre-Test by Surface Finish
(Acceptance Criterion = Resistance > 7.7 log_{10} ohms)

Figure 4-22. Boxplot Displays for PGA-B Measurements (log_{10} ohms) at Pre-Test by Surface Finish
(Acceptance Criterion = Resistance > 7.7 log_{10} ohms)

Figure 4-23. Boxplot Displays for the Gull Wing Measurements ($\log_{10}$ ohms) at Pre-Test by Surface Finish
(Acceptance Criterion = Resistance > 7.7 $\log_{10}$ ohms)

4.2   COST ANALYSIS

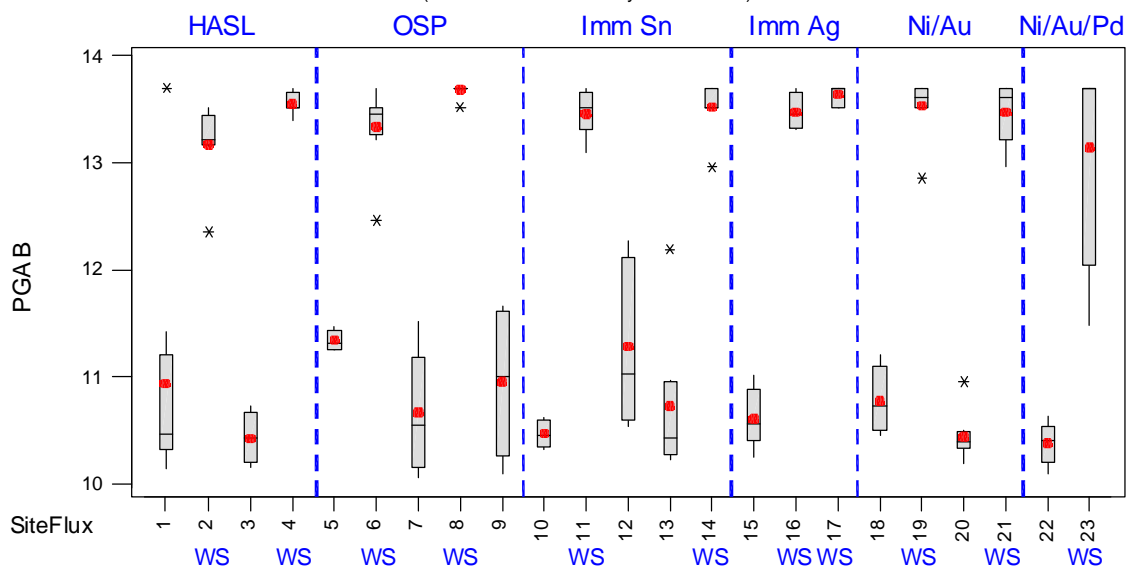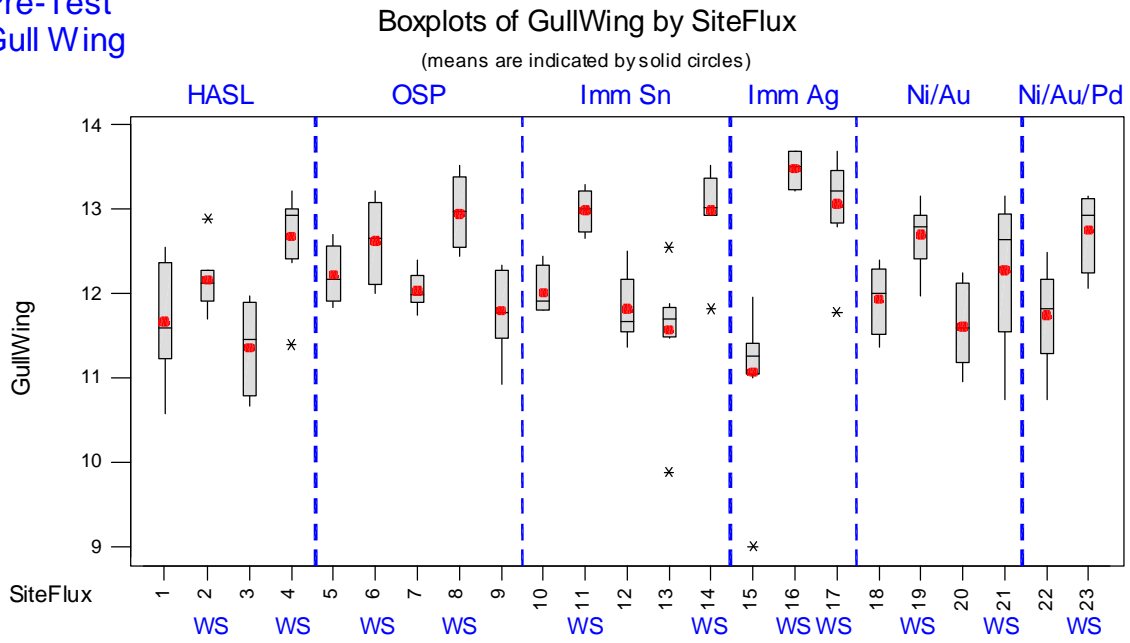Operating an efficient and cost-effective manufacturing process with strict control of material and production costs is the goal of every successful company. Consumer demand for smaller and lighter electronics is fueling rapid and continuous advancements in circuit technology, such as higher aspect-ratio holes and tighter circuit patterns. This in turn forces manufacturers to evaluate and replace aging manufacturing processes in order to keep up with the ever-increasing technology threshold. These new processes represent a major capital investment to a company, and emphasize the importance of selecting an efficient, cost-effective process that will allow the company to remain competitive. As a result, manufacturers are seeking comprehensive and more detailed cost data before investing in alternative processes.

This section presents a comparative cost analysis of the surface finishing technologies. Costs were developed for each technology and equipment configuration (vertical, immersion-type equipment; or horizontal, conveyorized equipment) for which data were available from the PWB Workplace Practices Questionnaire and Performance Demonstration. Table 4-30 presents the processes (alternatives and equipment configurations) evaluated.

Table 4-30. Surface Finishing Processes Evaluated in the Cost Analysis

Surface Finishing Alternative	Non-Conveyorized	Conveyorized
HASL	X	X
Nickel/Gold	X	
Nickel/Palladium/Gold	X	
OSP	X	X
Immersion Silver		X
Immersion Tin	X	X

Costs were analyzed using a cost model developed by the University of Tennessee Department of Industrial Engineering. The model employs generic process steps and functional groups (see Section 2.1, Chemistry and Process Description of Surface Finishing Technologies) to form a typical bath sequence (see Section 3.1, Source Release Assessment) for each process alternative. To develop comparative costs on a $/surface square foot (ssf) basis, the cost model was formulated to calculate the cost of performing the surface finishing function on a job consisting of 260,000 ssf (value corresponds to the average annual throughput for facilities using HASL in the PWB Workplace Practices Questionnaire database).

Processes were also modeled at a throughput of 60,000 ssf, a number which corresponds to the average annual throughput for facilities using a non-HASL alternative. This additional modeling run was performed to examine the effects, if any, that operating throughput will have on the normalized cost for each process. Although the calculations presented in this section are based on the higher production operating conditions, similar calculations were performed using lower production level data and the results of the two runs are compared at the end of the cost analysis.

The overall objective of this analysis was to determine the comparative costs of the surface finishing technologies using a cost model that adheres to fundamental principles of cost analysis. Other objectives were to make the analysis flexible and to consider environmental costs. The cost model was designed to estimate the comparative costs of fully operational surface finishing process lines. It does not estimate start-up costs for a facility switching to an alternative surface finishing technology or the cost of other process changes that may be required to implement a new surface finishing line. Section 4.2.1 gives an overview of the cost methodology used in this analysis. Section 4.2.2 presents the cost categories defined for the analysis and discusses the categories that could not be quantified. Section 4.2.3 presents an overview of the simulation model purpose, approach and results, while Section 4.2.4 describes the activity-based costing techniques and results. Section 4.2.5 details of the individual cost formulations and presents sample cost calculations. Section 4.2.6 contains analysis results and conclusions.

4.2.1   Overview of the Cost Methodology

The costs of the surface finishing technologies were analyzed by identifying the steps in each process, breaking each step down into its cost components, and determining the cost of each component. Component costs were determined using a combination of traditional costing mechanisms, computer simulation, and activity-based costing (ABC). Figure 4-24 presents the hybrid cost formulation framework:
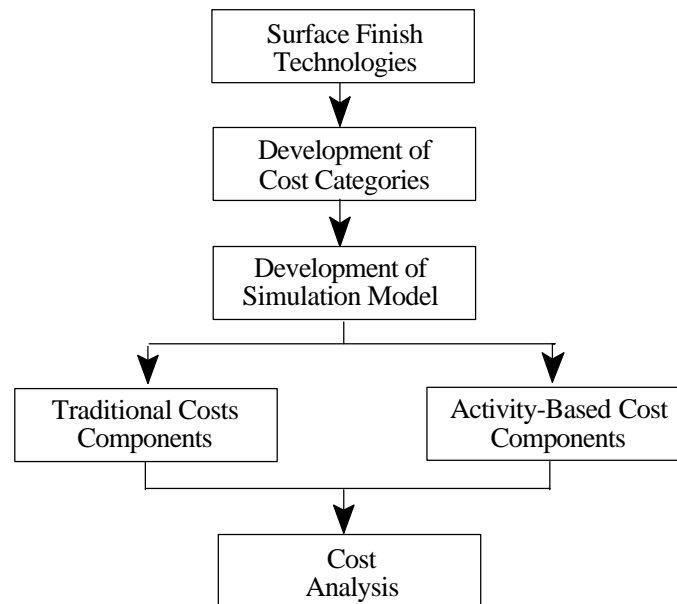

Figure 4-24. Hybrid Cost Analysis Framework

The generic process descriptions, chemical baths, typical bath sequences, and equipment configurations for each surface finishing process form the basis of the cost analysis and are presented in Table 4-30 and Figure 2-1 from Chapter 2, Profiling of the Surface Finishing Use Cluster. The process information was used to identify critical variables and to define the cost categories to be calculated by the cost analysis. The cost categories were analyzed to identify the data required to calculate the costs (e.g., unit costs; utilization or consumption rates; criteria for performing an activity, such as chemical bath replacement; the number of times an activity is performed). For each process, a computer simulation was developed using ARENA® computer simulation software. The simulation model then was used to model each process under similar operating conditions to determine operating data, such as overall production time, required by the cost analysis. Individual cost formulas were developed using traditional cost techniques, while costs typically allocated to overhead were quantified using ABC techniques. The costs were then calculated and compared to the cost of the baseline, non-conveyorized, HASL process. A more detailed description of each step is presented later in this chapter.

4.2.2   Cost Categories and Discussion of Unquantifiable Costs

<u>Cost Categories</u>

Table 4-31 summarizes the cost components considered in this analysis, gives a brief description of each cost component and key assumptions, and lists the primary sources of data for determining the costs. Section 4.2.5 gives a more detailed accounting of the cost components, including sample cost calculations for each component. In addition to traditional costs, such as capital, production, and maintenance costs, the cost formulation identifies and captures some environmental costs associated with the technologies. In this regard, both simulation and ABC assist in analyzing the impact of the surface finishing technologies on the environment. Specifically, the amounts of energy and water consumed, as well as the amount of wastewater generated, are determined for each surface finishing process.

<u>Unquantifiable Cost Categories</u>

The goal of this cost analysis was to perform a comparative cost analysis on the surface finishing alternatives in the evaluation. Although every effort was made to characterize each cost component listed in Table 4-31, data and/or process limitations prevented the quantification of every component. A qualitative discussion of each of these costs is presented below.

Table 4-31. Cost Component Categories

Cost Category	Component	Description of Cost Component	Sources of Cost Data
Capital Cost	Primary Equipment & Installation	Annualized cost of equipment with throughput capacity of 60 panels/hr x UR[a]; includes the cost of delivery and installation of equipment; assumes 10 year equipment life and straight-line depreciation.	Vendor quote for equipment and installation costs; time to complete job from simulation.
	Facility	Annualized cost of floor space required to operate surface finish process equipment x UR[a]; assumes 25 year facility life and straight-line depreciation.	Floor space requirements from IPC Workplace Practices Questionnaire; unit cost for industrial floor space from published sources.
Material Cost	Process Chemicals	Costs of chemicals used in initial bath setup, bath maintenance additions, and replacement of spent process baths.	Vendor quotes for chemical product cost; bath sizes from IPC Workplace Practices Questionnaire; bath replacement criteria from supplier data; number of bath replacements required for job from simulation.
Utility Cost	Water	Water consumption costs based on number of rinse stages per process line and normalized water flow rates per stage.	Number of rinse stages and normalized water flow rates per stage from Section 5.1, Resource Conservation; cost of water based on results reported by manufacturers from the Pollution Prevention and Control Survey.
	Electricity	Electricity costs based on daily electrical consumption of surface finish process equipment and days to complete job.	Daily electricity consumption from Section 5.2, Energy Impacts; days to complete job from simulation; cost of electricity based on national power grid from the Internal Energy Agency.
	Natural Gas	Natural gas consumption based on daily natural gas consumption from drying ovens and days to complete job.	Daily natural gas consumption from Section 5.2, Energy Impacts; days to complete job from simulation; cost of natural gas from the Knoxville Utilities Board (KUB).
Wastewater Cost	Publicly Owned Treatment Works (POTW) Permit	Cost for permit to discharge wastewater to POTW.	Not quantified; assumed to be the same for all alternatives.
	Wastewater Pretreatment Cost	Cost to pretreat wastewater prior to discharge to POTW.	Not quantified; pretreatment costs are expected to differ significantly among the alternatives, but inability to separate pretreatment of surface finish wastes from other process wastes made it impossible to reliably estimate these costs.
	Wastewater Discharge Costs	Fees for wastewater discharge assessed by local utility.	Quantity of wastewater discharged assumed equal to water usage; discharge fees based on fees charged by KUB.

Cost Category	Component	Description of Cost Component	Sources of Cost Data
Production Cost	Labor	Labor costs for line operator, excluding labor costs for maintenance activities (included under maintenance costs). Assumes one line operator per day per conveyorized process, 1.1 line operators per day per non-conveyorized process, to reflect the greater level of labor required.	Number of line operators based on IPC Workplace Practices Questionnaire data and site visits; days to produce job from simulation; labor rate based on published data.
	Transportation of Materials	Cost to transport chemicals required for bath replacement from storage to process line.	Cost of transporting materials from a bill of activity (BOA); number of bath replacements required from simulation.
Maintenance Cost	Bath Cleanup	Labor and material (excluding chemicals) costs to clean up a chemical tank during bath replacement.	Cost to clean up tank from BOA; number of bath cleanups (replacements) required from simulation.
	Bath Setup	Labor and equipment costs to set up a chemical tank after bath replacement.	Cost to set up bath from BOA; number of bath setups required from simulation.
	Sampling and Analysis	Labor and materials costs for sampling and analysis of chemical baths.	Assumes analytical work done in-house. Cost for one activity from BOA; annual number of samples from IPC Workplace Practices Questionnaire adjusted using UR[a].
	Filter Replacement	Labor costs for replacing bath filters.	Labor cost for one activity from BOA; annual number of filters replaced from IPC Workplace Practices Questionnaire adjusted using UR[a].
Waste Disposal Cost	Sludge Disposal	Disposal cost to recycle or disposal of sludge from wastewater treatment.	Not quantified; sludge disposal costs are expected to differ significantly among the alternatives, but insufficient data were available to reliably estimate these costs. Factors affecting sludge disposal cost include the characteristics of the sludge (e.g., type of metal content, percent solids, waste classification, etc.), the amount of sludge generated, and the type of disposal (e.g., reclaim, disposal to landfill, etc).
	Filter Disposal	Disposal cost to recycle or dispose of bath filters.	Not quantified; filter disposal costs are not expected to differ significantly among the alternatives, but insufficient data on the type and size of waste filters made it difficult to reliably estimate these costs. Factors affecting filter disposal cost include the waste classification of the filter, the size (weight and volume) of the filter, and the number of waste filters generated.
Quality Cost	Defective Boards	Costs of defective boards due to failure of the surface finish process line to apply an adequate finish to the surface of the PWB.	Not quantified; assumed equal among the alternatives. Performance Demonstration showed that all alternatives can work at least as well as the baseline process as long as they are operated according to supplier specifications.

[a] UR = utilization ratio = the time in days required to process 260,000 ssf ÷ one operating year (280 days).

Wastewater Treatment and Sludge Disposal Costs. PWB manufacturing consists of a number of process steps (see Section 1.2.3 for an overview of rigid multi-layer PWB manufacturing). In addition to the surface finishing process line, these steps include electroplating operations and other steps which consume large quantities of rinse water and, consequently, generate large quantities of wastewater. Most PWB manufacturers combine the effluents from various process lines into one wastewater stream which is treated on-site in a continuous process prior to discharge.

As part of the *Pollution Prevention and Control Survey* (U.S. EPA, 1998), PWB manufacturers were asked to provide the following about their on-site wastewater treatment facility:

- a process flow diagram for wastewater treatment;
- the quantity of sludge generated from wastewater treatment;
- the percent solids of the sludge;
- the costs of on-site wastewater treatment; and
- the method and costs of sludge recycle and disposal.

Capital costs for wastewater treatment ranged from $1.2 million for a system purchased in 1980 with a capacity of 135 gallons per minute (gpm) to $4,000 for a system purchased in 1987 with a capacity of nine gpm. Costs for operating an on-site wastewater treatment system were as high as 3.1 percent of total annual sales. The median cost for wastewater treatment operation was 0.83 percent, and the average was 1.02 percent of annual sales.

Wastewater treatment sludges from PWB electroplating operations are classified as an F006 hazardous waste under the Resources Conservation and Recovery Act (RCRA); most facilities combine effluents from the electroplating line with other process wastewaters. Eighty-eight percent of respondents to the Pollution Prevention and Control Survey reported that wastewater treatment sludges are sent to an off-site recycling facility to recover the metals. The average and median costs for off-site recovery of sludge were $0.48/lb and $0.21/lb, respectively. In general, the lower costs experienced by some respondents compared to others were due to larger-size shipments and shorter distances to the recycling sites. In some cases, respondents whose sludge had a higher solids content also reported lower costs; dewatered sludge has a higher recovery value.

The PWB Workplace Practices Questionnaire attempted to characterize costs by collecting information about the percentage contribution of the surface finishing line to the overall wastewater and sludge generation rates. However, most manufacturers were unable to provide this information and the data that were reported were of variable to poor quality.

A drag-out model was developed to determine the extent of chemical contamination of the wastewater resulting from drag-out. The model was used to estimate quantities of the chemical constituents in the wastewater. Model results are presented in Section 3.2, Exposure Assessment and Appendix E. However, since the streams are co-mingled prior to treatment, industry sources explained that it would be difficult to reliably quantify the effect of the surface finishing wastewater stream on the treatment of the entire stream (e.g., a treatment chemical used to treat the surface finishing wastewater may have a stronger affinity for another compound that may be present in the wastewater from another source, thus negatively affecting the treatment of the surface finishing wastewater).

Because the surface finishing line is only one of several process lines that discharge effluent to wastewater treatment, and because little or no information is available on the contribution of the surface finishing line to overall wastewater effluents, on-site wastewater treatment and sludge disposal costs could not be reliably estimated. However, costs of wastewater treatment and sludge disposal are expected to differ significantly among the alternatives, based on the compounds involved. For example, the presence of thiourea in the immersion tin process may require an additional treatment step to break down the compound prior to release. Silver is tightly regulated, thus the addition of an immersion silver process to a facility may require additional treatment to prevent exceeding the relatively low effluent limit. A detailed discussion of treatment concerns, systems, and options for each surface finishing process is presented in Section 6.2, Recycle, Recovery, and Control Technologies Assessment.

Other Solid Waste Disposal Costs. Two other types of solid wastes were identified among the technologies that could have significantly different waste disposal costs: filter disposal cost and defective boards disposal costs. Table 4-32 presents the number of filters that would be replaced in each process during a job of 260,000 ssf. This is based on data from the PWB Workplace Practices Questionnaire and a utilization ratio (UR) calculated for each process from simulation results (Simulation results are discussed further in Section 4.2.3). The UR is the percentage of time during the year required for the process to manufacture the required throughput. While these results illustrate that the number of waste filters generated by the processes differ significantly, no information is available on the characteristics of the filters used by the processes. For example, the volume or mass of the filters and waste classification of the filters (hazardous or non-hazardous) would significantly affect the unit cost for disposal. Therefore, filter disposal costs were not estimated.

The number of defective boards produced by a process has significance not only from the standpoint of quality costs, but also from the standpoint of waste disposal costs. Clearly, a higher defect rate leads to higher scrap and, therefore, waste of resources. However, the Performance Demonstration showed that each of the technologies can perform as well as the HASL process if operated according to specifications. Thus, for the purposes of this analysis, no differences would be expected in the defect rate or associated costs of the technologies.

Table 4-32. Number of Filter Replacements by Surface Finishing Process

Surface Finishing Process	Filter Replacements per Year [a]	Filter Replacements Required to Produce 260,000 ssf [b]
HASL, Non-conveyorized	354	55
HASL, Conveyorized	354	28
Nickel/Gold, Non-conveyorized	119	90
Nickel/Palladium/Gold, Non-conveyorized	162	162
OSP, Non-conveyorized	150	19
OSP, Conveyorized	150	9
Immersion Silver, Conveyorized	19.5	4
Immersion Tin, Non-conveyorized	150	40
Immersion Tin, Conveyorized	150	57

[a] 90th percentile data based on PWB Workplace Practices Questionnaire data. Data not adjusted for throughput or to account for differing maintenance policies at individual PWB manufacturing facilities.
[b] Values calculated by multiplying the filter replacements per year for a process by the utilization ratio for that process.

4.2.3 Simulation Modeling of Surface Finishing Processes

A computer simulation was developed using ARENA® computer simulation software for each surface finishing process. The purpose of the modeling is to simulate the operation of each process on the computer under identical conditions to predict a set of key metrics (e.g., overall production time, process down time, number of bath replacements) required to perform a comparative cost analysis. The model is necessary because the data collected from actual facilities, if available, would reflect the individual operating practices of each facility (e.g., bath maintenance frequencies, rise water flow rates, PWB feed rates) preventing a valid comparison of any process costs. Appendix G presents a graphic representation of the simulation models developed for each of the surface finishing technologies.

Simulation modeling provides a number of benefits to the cost analysis, including the following:

- Simulation modeling replicates a production run on the computer screen, allowing the analyst to observe a process when the actual process does not exist: in this case, the generic surface finishing technologies, as defined in Figure 2-1, may not exist within any one facility.
- Simulation allows for process-based modifications and variations, resulting in inherent flexibility within the system: models can be designed to vary the sequence of operations, add or delete operations, or change process times associated with operations, materials flows, and other variables.
- Simulation modeling facilitates the comparison of technologies by modeling each technology operating under a single, consistently applied performance profile developed from data collected from industry.

- Simulation enables a study of the sensitivity of critical performance measures to changes in underlying input variables (constant input variables may be modified in the sensitivity analysis to determine the uncertainty associated with these input variables).

Direct results of the simulation model and results derived from simulation outputs include the following:

- the overall time the surface finishing line operates to produce the job;
- the number of repetitions of an activity (e.g., bath replacements) over the course of the job;
- consumption rates (e.g., water, energy, and chemical consumption); and
- production rates (e.g., wastewater generation).

Simulation results were combined with traditional cost components to adjust these costs for the specified job. An example of this is the determination of equipment cost. Simulation results were used to calculate a UR, defined as the amount of time in days required to produce 260,000 ssf divided by one operating year. A 280-day operating year was selected to match the longest modeled operating time for any process (nickel/palladium/gold). Annualized equipment costs were determined using industry sources for equipment price and depreciation guidelines from the Internal Revenue Service. These costs were multiplied by the UR to determine the equipment costs for the job being evaluated.

Simulation Model Assumptions

Several assumptions used in the simulation model are based on the characteristics of a model facility presented in the Source Release Assessment and Exposure Assessment (Sections 3.1 and 3.2, respectively). Assumptions include the following:

- The facility operates a surface finishing process line 280 days/year, one shift/day; [Note: many facilities operate two shifts, but the Exposure Assessment and this analysis use first shift data as representative. This assumption could tend to underestimate labor costs for companies that pay higher rates to second shift workers. Alternatively, it could tend to overestimate equipment costs for a company running two shifts and using equipment more efficiently. However, because this assumption is used consistently across technologies, the effects on the comparative cost results are expected to be minor.]
- the surface finishing process line operates an average of 6.8 hr/shift;
- the surface finishing line is down at least 1.2 hr/day for start-up time and for maintenance, including lubricating of equipment, sampling of baths, and filter replacement;
- additional down time occurs when the surface finishing line is shut down to replace a spent or contaminated bath;
- PWB panels that have been processed up to the surface finishing step are available whenever the surface finishing process line requires them;
- if a chemical bath is replaced at the end of the day, and the amount of time required to replace the bath exceeds the time remaining in the shift hours, employees will stay after hours and have the bath ready by the beginning of the next shift;

- the entire surface finishing process line is shut down whenever a bath requires replacing, but partially processed racks or panels are finished before the line is shut down;
- the surface finishing process only shuts down at the end of a shift and for bath replacement, when required; and
- the process is empty of all panels or racks at the end of each shift, and starts the process empty at the beginning of a shift.

Further simulation assumptions have to be defined separately for conveyorized and non-conveyorized systems. Conveyorized surface finishing process assumptions are as follows:

- the size of a panel is 17.5 x 23.1" (from PWB Workplace Practices Questionnaire data for conveyorized processes);
- panels are placed on the conveyor whenever space on the conveyor is available, and each panel requires 18 inches (including space between panels);
- conveyor speed is constant, thus, the volume (gallons) of chemicals in a bath varies by bath type (i.e., microetch, conditioner, etc.) and with the length of the process step (e.g., bath or rinse tank) to provide the necessary contact time (see Table 4-33 for bath volumes); and
- the conveyor speed, cycle time, and process down time are critical factors that determine the time to complete a job.

Table 4-33. Bath Volumes Used for Conveyorized Processes

Chemical Bath	Bath Volume by Surface Finishing Alternative (gallons)			
	HASL	OSP	Immersion Silver	Immersion Tin
Cleaner	66.5	66.5	66.5	66.5
Microetch	86.6	86.6	86.6	86.6
Flux	13.2	NA	NA	NA
Solder	17.4	NA	NA	NA
OSP	NA	125	NA	NA
Predip	NA	NA	46.2	46.2
Immersion Silver	NA	NA	142	NA
Immersion Tin	NA	NA	NA	140

NA: Not applicable.

Non-conveyorized surface finishing process assumptions are as follows:

- the average volume of a chemical bath is 51.1 gallons (from PWB Workplace Practices Questionnaire data for non-conveyorized processes);
- only one rack of panels can be placed in a bath at any one time;
- a rack contains 20 panels (based on PWB Workplace Practices Questionnaire data, including the dimensions of a bath, the size of a panel, and the average distance between panels in a rack);

- the size of a panel is 4.22 ssf to give 84.4 ssf/rack;
- the frequency at which racks are entered into the process is dependent upon the bottleneck or rate limiting step; and
- the duration of the rate limiting step, cycle time, and process down time are critical factors that determine the time to complete a job.

Simulation Model Inputs Values

Input values for the critical factors identified above (cycle time, down time, and conveyor speed for conveyorized processes, and cycle time, down time, and duration of rate limiting step for non-conveyorized processes) were developed from the PWB Workplace Practices Questionnaire data and Product Data Sheets (Product Data Sheets, which are prepared by suppliers, describe how to mix and maintain chemical baths). Tables 4-34 and 4-35 present time-related inputs to the simulation models for non-conveyorized and conveyorized processes, respectively.

Table 4-34. Time-Related Input Values for Non-Conveyorized Processes [a]

Non-Conveyorized Surface Finishing Technology	Time Required to Replace a Bath [b] (minutes)	Rate Limiting Bath	Time in Rate Limiting Bath [b] (minutes)	Process Cycle Time [b] (minutes)
HASL	136	Cleaner	3.47	7.94
Nickel/Gold	116	Electroless Nickel	18.3	86.8
Nickel/Palladium/Gold	113	Electroless Nickel	18.3	109
OSP	149	Cleaner	3.47	22.6
Immersion Tin	85	Immersion Tin	8.55	27.0

[a] Values may represent chemical products from more than one supplier. For example, two suppliers of nickel/gold chemical products participated in the project. Input values may underestimate or overestimate those of any one facility, depending on factors such as individual operating procedures, the chemical or equipment supplier, and the chemical product used.
[b] Average values from the PWB Workplace Practices Questionnaire and Performance Demonstration observer sheets.

Table 4-35. Time-Related Input Values for Conveyorized Processes [a]

Conveyorized Surface Finishing Technology	Time Required to Replace a Bath [b] (minutes)	Length of Conveyor [b] (feet)	Process Cycle Time [b] (minutes)	Conveyor Speed [c] (ft/min)
HASL	136	41.3	4.86	8.50
OSP	149	54.1	5.22	10.4
Immersion Silver	114	34.0	11.2	3.04
Immersion Tin	85	20.0	12.3	1.63

[a] Values may represent chemical products from more than one supplier. For example, two suppliers of OSP chemical products participated in the project. Input values may underestimate or overestimate those of any one facility, depending on factors such as individual operating procedures, the chemical or equipment supplier, and the chemical product used.
[b] Average values from PWB Workplace Practices Questionnaire and Performance Demonstration observer sheets.
[c] Conveyor speed was calculated by dividing the length of conveyor by the process cycle time.

The input values for the time required to replace a bath (in Tables 4-34 and 4-35) are used together with bath replacement criteria in the calculation of down time. Suppliers provide instructions with their products (called Product Data Sheets for the purposes of this project) that describe when a bath should be replaced because it is expected to be spent or too contaminated to be used. These replacement criteria are usually given in one of four forms:

- as a bath production capacity in units of ssf per gallon of bath;
- as a concentration-based criterion that specifies an upper concentration limit for contaminants in the bath, such as grams of copper per liter in the microetch bath;
- as elapsed time since bath make-up; or
- as a number of chemistry (or metal) turnovers before replacement.

Bath replacement criteria submitted by suppliers were supplemented with PWB Workplace Practices Questionnaire data and reviewed to determine average criteria for use in the simulation models. Criteria in units of ssf/gallon were preferred because these could be correlated directly to the volume of a bath. For baths with replacement criteria expressed in number of chemical turnovers, the ssf/gallon for that bath was adjusted by a factor equal to the number of metal turnovers (e.g., the replacement criteria for a 750 ssf/gal bath with two metal turnovers was considered to be 1500 ssf/gal of bath). Table 4-36 presents bath replacement criteria used to calculate input values for the nickel/gold processes, as an example. Appendix G presents the bath replacement criteria recommended by chemical suppliers, and the input values used in this analysis for the remaining surface finishing technologies.

Table 4-36. Bath Replacement Criteria for Nickel/Gold Processes

Chemical Bath	Bath Replacement Criteria [a] (ssf/gal)
Cleaner	750
Microetch	570
Catalyst	830
Acid Dip	1500
Electroless Nickel	130
Immersion Gold	890

[a] Values were selected from data provided by two nickel/gold suppliers. To convert to units of racks per bath replacement for non-conveyorized processes, multiply by 51.1 gallons (the average bath size) and divide by 84.4 ssf (ssf per rack). To convert to units of panels per bath replacement for conveyorized processes, multiply by the bath size in gallons and divide by 5.66 ssf/panel.

Simulation Model Results

Simulation models were run for each of the surface finishing processes. Simulation outputs used in the cost analysis include:

- frequency and duration of bath replacements;
- overall production time required for each process; and
- down time incurred while producing 260,000 ssf.

For example, the frequency and duration of bath replacements for nickel/gold that were obtained from the simulation modeling are shown in Table 4-37. The frequency of bath replacements for each bath type was calculated by the simulation model using the bath replacement criteria presented for each bath in Table 4-36. Using the average time of bath replacement determined from the PWB Workplace Practices Questionnaire data, the total down time associated with the replacement of each bath type was determined. Summing over all baths, bath replacement consumed 36.7 hours (2,200 minutes) to produce 260,000 ssf when using the non-conveyorized nickel/gold process. Bath replacement simulation outputs for the other surface finishing processes are presented in Appendix G.

Table 4-37. Frequency and Duration of Bath Replacements for Non-Conveyorized Nickel/Gold Process

Chemical Bath	Frequency of Replacement	Avg. Time of Replacement (minutes)	Total Time of Replacement (minutes)
Cleaner	7	116	812
Microetch	9	116	1,044
Catalyst	6	116	696
Acid Dip	4	116	464
Electroless Nickel	40	116	4,640
Immersion Gold	6	116	696
Total	**72**	**116**	**8,352**

Table 4-38 presents the other simulation outputs: the total production time required and the down time incurred by the surface finishing processes while producing 260,000 ssf of PWB. Total production time is the sum of actual operating time and down time. The operating time is based on the process producing 260,000 ssf of PWB and operating 6.8 hr/day. The down time includes the remaining 1.2 hr/day that the line is assumed inactive, plus the time the process is down for bath replacements. The amount of process down time due to a bath replacement, shown in Table 4-37, may be adjusted by the model if the bath changeout occurs at the end of the day, when the replacement duration exceeds the time remaining in the day. (7,670 minutes of downtime are reported in Table 4-38, indicating that 680 minutes of the 8,352 reported in Table 4-37 occurred at the end of the day.) In this instance, the worker is considered to complete the bath replacement during the remaining 1.2 hours of the day set aside for process maintenance. The simulation model output reports for each process are presented in Appendix G.

Table 4-38. Production Time and Down Time for the Surface Finishing Processes to Produce 260,000 ssf of PWB

Surface Finishing Process	Total Production Time [a]		Total Down Time [a]	
	minutes	days	minutes	days
HASL, Non-conveyorized	17,830	43.7	2,330	5.7
HASL, Conveyorized	8,890	21.8	938	2.3
Nickel/Gold, Non-conveyorized	86,500	212	7,670	18.8
Nickel/Palladium/Gold, Non-conveyorized	114,240	280	11,380	27.9
OSP, Non-conveyorized	14,360	35.2	2,530	6.2
OSP, Conveyorized	6,570	16.1	1,020	2.5
Immersion Silver, Conveyorized	26,190	64.2	1,390	3.4
Immersion Tin, Non-conveyorized	30,680	75.2	1,880	4.6
Immersion Tin, Conveyorized	43,660	107	1,020	2.5

[a] To convert from minutes to days, divide by 6.8 hr/day (408 minutes).

4.2.4 Activity-Based Costing

ABC is a method of allocating indirect or overhead costs to the products or processes that actually incur those costs. ABC complements the traditional costing /modeling efforts of this assessment by allowing the cost of tasks that are difficult to quantify, or are just unknown by industry, to be determined. Activity-based costs are determined by developing a BOA for critical tasks, which are defined as tasks required to that support the operation of the surface finish process line. A BOA is a listing of the component activities involved in the performance of a certain task, together with the number of times each component activity is performed. The BOA determines the cost of a task by considering the sequence of actions and the resources utilized while performing that task. In this analysis, the costs of critical tasks determined by a BOA are combined with the number of times a critical task is performed, derived from simulation results to determine the total costs of that activity.

BOAs were developed for the following critical tasks performed during the operation of the surface finishing process:

- chemical transport from storage to the surface finishing process;
- tank cleaning;
- bath setup;
- bath sampling and analysis; and
- filter replacement.

These BOAs were developed based on information developed for earlier projects involving similar tasks and on information gathered through site visits and general process knowledge. The following discussion uses the BOA for chemical transport, presented in Table 4-39, as an example of how BOAs were developed and used. Appendix G presents the BOAs for the remaining activities.

Key assumptions were developed to set the limits and to designate the critical activity's characteristics. For chemical transport, the assumptions were as follows:

- chemical costs are not included in the BOA, but are considered within material costs;
- labor costs considered are independent of those included within production costs;
- employee labor rate is $10.24 per hour, consistent with the rate for an operator-level job;
- multiple chemicals are required for each bath replacement;
- all chemicals for a bath replacement are transported on one forklift trip;
- chemicals are purchased in containers larger than the line containers used to move chemicals to the surface finishing process;
- all chemicals are stored in a central storage location;
- chemicals are maintained in central storage via inventory tracking and physical monitoring;
- forklift operation costs are $580/month or $0.06/minute, which includes leasing, maintenance, and fuel;
- forklifts are used to move all chemicals; and
- forklifts are parked in an assigned area when not in use.

Each critical task was broken down into primary and secondary activities. For example, chemical transport has six primary activities: paperwork associated with chemical transfer, moving forklift to chemical storage area, locating chemicals in storage area, preparation of chemicals for transfer, transporting chemicals to the surface finishing process, and transporting chemicals from the surface finishing process to the bath. The secondary activities for the primary activity of "transport chemicals to the surface finishing process" are: move forklift with chemicals, unload line containers, and park forklift in assigned parking area. For each secondary activity the labor, material, and forklift costs are calculated. The forklift costs are a function of the time that labor and the forklift are used. On a BOA, the sum of the costs of a set of secondary activities equals the cost of the primary activity.

Continuing the example, for a chemical transport activity that requires two minutes, the labor cost is $0.34 (based on a labor rate of $10.24/hour) and the forklift cost is $0.12 (based on $0.06/minute). Materials costs are determined for materials other than chemicals and tools required for an activity. The total of $9.28 shown in Table 4-39 represents the cost of a single act of transporting chemicals to the surface finishing line. The same BOAs are used for all surface finishing technologies because either the activities are similar over all technologies or information is unavailable to distinguish between them. However, individual facilities could modify a BOA to best represent their unique situations. Table 4-40 presents costs to perform each of the critical tasks one time.

Table 4-39. BOA for Transportation of Chemicals to the Surface Finishing Process Line

Activities	Time (min)	Resources			Cost ($/transport)
		Labor [a]	Materials [b]	Forklift [c]	
A. Paperwork and Maintenance					
1. Request for chemicals	2	$0.34	$0.10	$0.00	$0.44
2. Updating inventory logs	1	$0.17	$0.05	$0.00	$0.22
3. Safety and environmental record keeping	2	$0.34	$0.10	$0.00	$0.44
B. Move Forklift to Chemical Storage Area					
1. Move to forklift parking area	2	$0.34	$0.00	$0.12	$0.46
2. Prepare forklift to move chemicals	5	$0.85	$0.00	$0.30	$1.15
3. Move to line container storage area	2	$0.34	$0.00	$0.12	$0.46
4. Prepare forklift to move line container	3	$0.51	$0.00	$0.18	$0.69
5. Move forklift to chemical storage area	2	$0.34	$0.00	$0.12	$0.46
C. Locate Chemicals in Storage Area					
1. Move forklift to appropriate areas	1	$0.17	$0.00	$0.06	$0.23
2. Move chemical containers from storage to staging	2	$0.34	$0.00	$0.12	$0.46
3. Move containers from staging to storage	2	$0.34	$0.00	$0.12	$0.46
D. Preparation of Chemicals for Transfer					
1. Open chemical container(s)	1	$0.17	$0.05	$0.00	$0.22
2. Utilize correct tools to obtain chemicals	3	$0.51	$0.05	$0.00	$0.56
3. Place obtained chemicals in line container(s)	3	$0.51	$0.00	$0.00	$0.51
4. Close chemical container(s)	1.5	$0.26	$0.00	$0.00	$0.26
5. Place line container(s) on forklift	1	$0.17	$0.00	$0.06	$0.23
E. Transport Chemicals to Line					
1. Move forklift to line	2	$0.34	$0.00	$0.12	$0.46
2. Unload line container(s) at line	1	$0.17	$0.00	$0.06	$0.23
3. Move forklift to parking area	2	$0.34	$0.00	$0.12	$0.46
F. Transport Chemicals from Line to Bath					
1. Move line container(s) to bath	1	$0.17	$0.00	$0.00	$0.17
2. Clean line container(s)	2	$0.34	$0.20	$0.00	$0.54
3. Store line container(s) in appropriate area	1	$0.17	$0.00	$0.00	$0.17
Total Cost per Transport					**$9.28**

[a] Labor rate = $10.24 per hour.
[b] Materials do not include chemicals or tools.
[c] Forklift operating cost = $0.06 per minute.

Table 4-40. Costs of Critical Tasks

Task	Cost
Transportation of Chemicals	$9.28
Tank Cleaning	$67.00
Bath Setup	$15.10
Sampling and Analysis	$3.70
Filter Replacement	$17.50

4.2.5 Cost Formulation Details and Sample Calculations

This section develops and describes in detail the cost formulation used for evaluating the surface finishing process alternatives. The overall cost was calculated from individual cost categories that are common to, but expected to vary with, the individual process alternatives. The cost model was validated by cross-referencing the cost categories with Tellus Institute (White et al., 1992), and Pacific Northwest Pollution Prevention Research Center (Badgett et al., 1995).

The cost model for an alternative is as follows:

$$TC = C + M + U + WW + P + MA$$

where,

TC	=	total cost to produce 260,000 ssf
C	=	capital cost
M	=	material cost
U	=	utility cost
WW	=	wastewater cost
P	=	production cost
MA	=	maintenance cost

The unit cost of producing 260,000 ssf is then represented as follows:

$$\text{Unit Cost (\$/ssf)} = TC (\$) / 260,000 \text{ ssf}$$

The following sections present a detailed description of cost calculation methods together with sample calculations, using the non-conveyorized nickel/gold process as an example. Cost summary tables for all of the process alternatives are presented at the end of this section.

Capital Costs

This section presents methods and sample calculations for calculating capital costs. Capital costs are one-time or periodic costs incurred in the purchase of equipment or facilities. In this analysis, capital costs include the costs of primary equipment including equipment installation, and facility space utilized by the surface finishing process line. Primary equipment is the equipment vital to the operation of the surface finishing process without which the process

would not be able to operate (i.e., bath tanks, heaters, rinse water system, etc.). Installation costs include costs to install the process equipment and prepare it for production. Facility space is the floor space taken up by the actual process equipment plus an additional buffer area necessary for operation of the equipment by workers and access for maintenance and repair.

Total capital costs for the surface finishing processes were calculated as follows:

$$C = (E + I + F) \times UR$$

where,

E = annualized capital cost of equipment ($/yr)

I = annualized capital cost of installation ($/yr), which is sometimes included in the cost of the equipment

F = annualized capital cost of facility ($/yr)

UR = utilization ratio, defined as the time in days required to manufacture 260,000 ssf divided by one operating year (280 days)

The UR adjusts annualized costs for the amount of time required to process 260,000 ssf, determined from the simulation model for each process alternative. The components of capital costs are discussed further below followed by sample calculations of capital costs.

Equipment and Installation Costs. Primary equipment and installation cost estimates were provided by equipment suppliers and include delivery of equipment, installation, and sales tax. Equipment estimates were based on basic, no frills equipment capable of processing the modeled throughput rates determined by the simulation model, presented in Table 4-38. Equipment estimates did not include auxiliary equipment, such as statistical process control or automated sampling equipment sometimes found on surface finishing process lines.

Annual costs of the equipment (which includes installation) were determined assuming 5-year, straight-line depreciation and no salvage value. These annual costs were calculated using the following equation:

$$E = \text{equipment cost (\$)} \div 5 \text{ years}$$

Facility Costs. Facility costs are capital costs for the floor space required to operate the surface finishing line. Facility costs were calculated assuming industrial floor space costs $76/ft^2 and the facility is depreciated over 25 years using straight-line depreciation. The cost per square foot of floor space applies to Class A light manufacturing buildings with basements. This value was obtained from the Marshall Valuation Service (Vishanoff, 1995) and mean square foot costs (Ferguson, 1996). Facility costs were calculated using the following equation:

$$F = [\text{unit cost of facility utilized (\$/ft}^2) \times \text{footprint area/process step (ft}^2/\text{step}) \times \text{number of steps}] \div 25 \text{ years}$$

The "footprint area" is the area of floor space required by surface finishing equipment, plus a buffer zone to maneuver equipment or have room to work on the surface finishing process line, and to maintain and repair it.[2] The footprint area per process step was calculated by determining the equipment dimensions of each process alternative, adjusting the dimensions for working space, and then determining the area per process step. Because the footprint area depends on the type of process automation, the average dimensions of both conveyorized (8' x 40') and non-conveyorized (5' x 23') equipment, irrespective of surface finish technology, were determined from the PWB Workplace Practices Questionnaire data. Because these dimensions account for the equipment only, an additional 8 ft was added to every dimension to allow space for line operation, maintenance, and chemical handling. The footprint area required by either equipment type, including the buffer zone, was calculated as 1,344 ft^2 for conveyorized processes and 819 ft^2 for non-conveyorized processes. The area required per process step was determined by first identifying the process alternative with the fewest process steps for each automation type, and then dividing the required floor space by that number of steps. This method conservatively estimated the amount of floor space required per process step for conveyorized processes as 168 ft^2/step, and for non-conveyorized processes as 91 ft^2/step. The overall area required for each process alternative was then calculated using the following equations:

Conveyorized:

$$F_C = [\$76/\text{ft}^2 \text{ x } 168 \text{ ft}^2/\text{step x number of steps per process}] \div 25 \text{ years}$$

Non-conveyorized:

$$F_N = [\$76/\text{ft}^2 \text{ x } 91 \text{ ft}^2/\text{step x number of steps per process}] \div 25 \text{ years}$$

Example Capital Cost Calculations. This section presents example capital costs calculations for the non-conveyorized nickel/gold process. From Figure 2-1, the non-conveyorized nickel/gold process consists of 14 chemical bath and rinse steps. Simulation outputs in Table 4-38 indicate this process takes 212 days to manufacture 260,000 ssf of PWB. Equipment vendors estimated equipment and installation costs at a combined \$48,000 (Harbor, 2000). The components of capital costs are calculated as follows:

$E = \$48,000 \div 5 \text{ yrs} = \$9,600/\text{yr}$
$F_N = (\$76/\text{ft}^2 \text{ x } 91 \text{ ft}^2/\text{step x } 14 \text{ steps}) \div 25 \text{ yr} = \$3,870/\text{yr}$
$UR = 212 \text{ days} \div 280 \text{ days/yr} = 0.757 \text{ yr}$

Thus, the capital costs for the non-conveyorized nickel/gold process to produce 260,000 ssf of PWB are as follows:

$C = (\$9,600/\text{yr} + \$3,870/\text{yr}) \text{ x } 0.757 \text{ yr} = \$10,200$

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[2] PWB manufacturers and their suppliers use the term "footprint" to refer to the dimensions of process equipment, such as the dimensions of the surface finishing process line.

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Material Costs

Materials costs were calculated for the chemical products consumed during the operation of the surface finishing process lines, through the initial setup and subsequent replacement of process chemical baths. The following presents equations for calculating materials costs, along with some sample materials cost calculations.

Materials Cost Calculation Methods. Chemical suppliers were asked to provide estimates of chemical costs ($/ssf), along with the other process data required by the project. While some suppliers furnished estimates for one or more of their process alternatives, several suppliers did not provide chemical cost estimates for any of their surface finishing process lines being evaluated. Still others provided incomplete cost estimates, or did not provide any supporting documentation of assumptions used to estimate chemical costs. Therefore, these data could not be used in the comparative cost estimates. Instead, chemical costs were estimated using the methods detailed below.

Chemical baths are typically made up of one or more separate chemical products mixed together at specific concentrations to form a chemical solution. As PWBs are processed by the surface finishing line, the chemical baths become contaminated or depleted and require chemical additions or replacement. Baths are typically replaced according to analytical results or by supplier recommended replacement criteria specific to each bath. When the criteria are met or exceeded, the spent bath is removed and a new bath is created. The chemical cost to replace a specific bath one time is the sum of the costs of each chemical product in the bath, and is given by the following equation:

$$\text{Cost per bath replacement} = \sum_{I=1}^{n} [\text{chemical product I cost/bath (\$/gal) x}$$

% chemical product I in bath x total volume of bath (gal)]

where,
n   =   number of chemical products in a bath

Price quotes were obtained from chemical suppliers in $/gallon or $/lb for process chemical products. Chemical compositions of the individual process baths were determined from the corresponding Product Data Sheets submitted by the chemical suppliers of each process alternative. The average volume of a chemical bath for non-conveyorized processes was calculated to be 51.1 gallons from PWB Workplace Practices Questionnaire data. For conveyorized processes, however, conveyor speed is constant; thus, the volume of chemicals in a bath varies by bath type to provide the necessary contact time (see Table 4-33 for conveyorized process bath volumes). These data were used in the above equation to calculate the chemical cost per bath replacement for each product line. The bath replacement costs were then averaged across like product lines (e.g., chemical costs from various suppliers of the OSP were averaged by bath type) to determine an average chemical cost per replacement for each process bath.

To obtain the total materials cost, the chemical cost per bath replacement for each bath was multiplied by the number of bath replacements required (determined by simulation) and then summed over all the baths of an alternative process. The cost of chemical additions was not included, because no data were available to determine the amount and frequency of chemical additions. However, for process baths that are typically maintained rather than replaced (e.g., baths with expensive metal ions such as tin, gold, silver and palladium), the replacement criteria were adjusted to reflect the number of bath chemical turnovers that occur between bath replacements, thereby accounting for the additional chemical usage. A complete change of bath chemistry through bath maintenance, such as chemical additions, was considered one chemical turnover. The number of chemical turnovers for each bath is represented on Table 4-41 as the multiplying factor. Materials costs (M) are given by the following equation:

$$M = \sum_{j=1}^{m} [\text{chemical cost j /bath replacement (\$) x number of replacements/bath}]$$

where,
m   =   number of baths in a process

The frequency of replacement for individual process baths was determined using supplier recommended criteria provided on Product Data Sheets and from PWB Workplace Practices Questionnaire data. Simulation models were used to determine the number of times a bath would be replaced during the production of 260,000 ssf of PWB by the surface finishing process. Appendix G presents bath replacement criteria used in this analysis and summaries of chemical product cost by supplier and by surface finishing technology.

Example Materials Cost Calculations. Table 4-42 presents an example of chemical costs per bath replacement for one of the two nickel/gold product lines that were submitted by chemical suppliers for evaluation. From the data in the table, the total cost of chemicals per bath was calculated by multiplying the average chemical cost for a bath (calculated by computing the chemical cost per bath of the second product line not shown in Table 4-42, then averaging the costs for a bath from both product lines) by the number of bath replacements required to process 260,000 ssf, as determined by the process simulation. The costs for each bath were then summed to give the total materials cost for the overall non-conveyorized nickel/gold product line. Data for each of the product lines submitted, including the other electroless nickel/immersion gold product line, are presented in Appendix G.

Table 4-41 presents the chemical cost per bath replacement, the number of bath replacements required, as determined by simulation, the total chemical cost per bath, and the total material cost for the non-conveyorized nickel/gold process. The chemical costs per process bath for both product lines were averaged to determine the average chemical cost per bath for the non-conveyorized nickel/gold process. Similar material cost calculations are presented in Appendix G for each of the surface finishing process alternatives.

Table 4-41. Materials Cost for the Non-Conveyorized Nickel/Gold Process

Bath	Chemical Cost/Bath Replacement [a]	Number of Bath Replacements [b]	Total Chemical Cost
Cleaner	$92.80	7	$649
Microetch	$386	9	$3,470
Catalyst	$1,640	6	$9,830
Acid Dip	$315	4	$1,260
Electroless Nickel	$890	40	$35,500
Immersion Gold	NA [c]	6	$57,900
Total Materials Cost			**$108,600**

[a] Reported data represents the chemical cost per bath replacement averaged from two nickel/gold product lines.
[b] Number of bath replacements required to process 260,000 ssf, as determined by process simulation.
[c] The immersion gold replacement cost was calculated differently than the other baths because of the wide disparity in costs and throughput between product lines. The overall cost for the gold bath was calculated for each product line and then averaged together to give the gold chemical cost for the process.

Table 4-42. Chemical Cost per Bath Replacement for One Product Line of the Non-Conveyorized Nickel/Gold Process

Bath	Chemical Product	Product Cost [a] ($)	Percentage of Chemical Product [b]	Multiplying Factor [c]	Chemical Cost/Bath Replacement [d] ($)
Cleaner	A	$25.0/gal	10	1	$128
Microetch	B	$5.66/gal	3	1	$266
	C	$9.39/gal	3	1	
	D	$27.3/kg	45 g/l	1	
	E	$1.20/gal	8.5	1	
Catalyst	F	$127/gal	30	1	$2,810
	G	$54.0/gal	20	1	
	H	$51.0/gal	12	1	
Acid Dip	I	$29.1/kg	2 g/l	1	$11.3
Electroless Nickel	J	$24.1/gal	6.6	6	$2,390
	K	$30.9/gal	15	6	
	L	$28.4/gal	6.6	5	
Immersion Gold	M	$21.4/gal	50	1	$70,200
	N	$40.0/g	3 g/l	3	

[a] Product cost from supplier of the chemical product.
[b] The percentage of a chemical product by volume in each process bath was determined from Product Data Sheets provided by the supplier of the chemical product.
[c] Multiplying factors reflect the number of chemical turnovers expected before the bath is replaced. A chemical turnover is considered to be a complete change of bath chemistry through bath maintenance such as chemical additions. Multiplying factors are used for baths that are typically maintained, rather than replaced.
[d] Cost per bath calculated assumes a bath volume of 51.1 gallons, as determined by PWB Workplace Practices Questionnaire data for non-conveyorized processes.

Utility Costs

Utility costs for the surface finishing process include water consumed by rinse tanks,[3] electricity used to power the panel transportation system, heaters and other process equipment, and natural gas consumed by drying ovens employed by some process alternatives. The following example presents utility costs calculation methods and utility costs for the nickel/gold process.

Utility Cost Calculation Methods. The rate of water consumption depends on both the number of distinct water rinse steps and the flow rate of the water used in those steps. The typical number of water rinse steps for each surface finishing alternative was determined using supplier- provided data together with data from the PWB Workplace Practices Questionnaire. Based on Questionnaire data, the average normalized water flow rate per rinse stage for individual rinse types was 0.176 gal/ssf for conveyorized processes, 0.258 gal/ssf for non-conveyorized processes, and 0.465 gal/ssf for high pressure rinse tanks, regardless of automation type. However, it was assumed that the rinse steps are shut off during periods of process down time. Therefore, daily water consumption rates were adjusted for the percentage of time the process was in operation. The total volume of water consumed was calculated by multiplying the number of each type of rinse tank occurring in the process by the appropriate water flow rates for each rinse. Water consumption rates for surface finishing technologies, along with a detailed description of the methodology used to calculate them, are presented in Section 5.1, Resource Conservation.

The cost of water was calculated by multiplying the water consumption rate of the entire surface finishing process by the unit cost factor for water. A unit cost of $2.19/1,000 gallons of water was obtained from the *Pollution Prevention and Control Survey* (U.S. EPA, 1998). The equation for calculating water cost (W) is:

$$W = \text{quantity of rinse water consumed (gal)} \times \$2.19/1,000 \text{ gal}$$

The rate of electricity consumption for each surface finishing alternative is dependent upon the equipment required to operate each alternative. Differences in required process equipment, such as the number of heaters, pumps, and type and extent of panel agitation, directly affect electricity consumption. The cost of electricity is calculated by multiplying the electricity consumption rate of the process alternative by the production time required to produce 260,000 ssf of PWB, and then applying a unit cost factor to the total. Electricity consumption rates for surface finishing alternatives are presented in Section 5.2, Energy Impacts, while the required production time was determined by the simulation model. A unit cost of $0.069/kW-hr was obtained from the International Energy Agency. The energy cost (E) was calculated using the following equation:

$$E = \text{hourly consumption rate (kW)} \times \text{required production time (hr)} \times \$0.069/kW\text{-hr}$$

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[3] Water is also used in surface finishing chemical baths to dilute chemical products to the appropriate concentration, but this use of water was assumed negligible compared to the water consumed in rinse tanks.

Natural gas is used to fire the drying ovens required by many of the surface finishing processes. All processes with the exception of the nickel/gold and the nickel/palladium/gold processes required gas-fired ovens for panel drying. The amount of gas consumed was determined by multiplying the natural gas consumption rate for the process alternative by the amount of operating time required by the process to produce 260,000 ssf of PWB, and then applying a unit cost to the result. Knoxville Utilities Board (KUB) charges $0.4028 per therm of natural gas consumed (KUB, 2000a), while the production time required to produce 260,000 ssf of PWB came from simulation results. Thus, the cost of natural gas consumption (G) was calculated by the following equation:

$$G \ = \ \text{natural gas consumption rate (therm/hr) x required production time (hrs) x \$0.4028/therm}$$

The total utility cost (U) for a surface finishing process was determined as follows:

$$U \ = \ W + E + G$$

where,

W	=	cost of water consumed ($/ssf) to produce 260,000 ssf
E	=	cost of electricity consumed ($/ssf) to produce 260,000 ssf
G	=	cost of natural gas consumed ($/ssf) to produce 260,000 ssf

Example Utility Cost Calculations. The above methodology was used to calculate the utility costs for each of the surface finishing alternatives. This section presents example utility cost calculations for the non-conveyorized nickel/gold process.

Simulation results indicate the non-conveyorized nickel/gold process is down 18.8 days and takes 212 days overall (at 6.8 hrs/day) to produce 260,000 ssf. It is comprised of eight rinse steps which consume approximately 537,000 gallons of water during the course of the job (see Section 5.1, Resource Conservation). Electricity is consumed at a rate of 26.0 kW-hr of operation (see Section 5.2, Energy Impacts). The non-conveyorized nickel/gold process has no drying ovens and, therefore, does not consume natural gas. Based on this information, water, electricity, and gas costs were calculated as follows:

$$W \ = \ 537,000 \text{ gallons x \$2.19/1,000 gal} \ = \ \$1,180$$
$$E \ = \ 26.0 \text{ kW x (212 days - 18.8 days) x 6.8 hr/day x \$.069/kW-hr} \ = \ \$2,360$$
$$G \ = \ \$0$$

Thus, the utility cost for the process was determined by the calculation:

$$U \ = \ \$1,180 + \$2,360 + \$0 \ = \ \$3,540$$

<u>**Wastewater Costs**</u>

Wastewater Cost Calculation Method. Wastewater costs for the surface finishing processes were only determined for the cost of discharging wastewater to a POTW. The analysis assumes that discharges are made in compliance with local allowable limits for chemical concentrations and other parameters so that no fines are incurred.

Wastewater quantities were assumed equal to the quantity of rinse water used. Rinse water usage was calculated in Section 5.1, Resource Conservation, and used to calculate water costs in the Utility Costs section. The unit costs for fees charged by a POTW for both city and non-city discharges of wastewater were obtained from KUB, and were averaged for use in calculating wastewater cost (KUB, 2000b). These average unit costs are not flat rates applied to the total wastewater discharge, but rather combine to form a tiered cost scale that applies an incremental unit cost to each level of discharge. The tiered cost scale for wastewater discharges to a POTW is presented in Table 4-43.

Table 4-43. Tiered Cost Scale for Monthly Wastewater Discharges to a POTW

Wastewater Discharge Quantity (ccf/month)	City Discharge Cost ($/ccf/month)	Non-City Discharge Cost ($/ccf/month)	Average Discharge Cost ($/ccf/month)
0 - 2	$6.30	$7.40	$6.85
3 - 10	$2.92	$3.21	$3.06
11 - 100	$2.59	$2.85	$2.72
101 - 400	$2.22	$2.44	$2.33
401 - 5,000	$1.85	$2.05	$1.95

Source: KUB, 2000b.
ccf: 100 cubic ft.

The unit costs displayed for each level of discharge are applied incrementally to the quantity of monthly discharge. For example, the first two cubic feet of wastewater discharged in a month are assessed a charge of $6.85, while the next eight cubic feet cost $3.06, and so on. The production time required to produce 260,000 ssf of PWB comes from the simulation models. Thus, wastewater costs (WW) were calculated as follows:

$$WW = \sum_{k=1}^{p} [\text{quantity of discharge in tier k (ccf/mo) x tier cost factor (\$/ccf)}] \times \text{required production time (months)}$$

where,
p   =   number of cost tiers
ccf   =   100 cubic ft

Example Wastewater Cost Calculations. This section presents example wastewater calculations for the non-conveyorized nickel/gold process. Based on rinse water usage, the total wastewater release was approximately 537,000 gallons. The required production time in months was calculated using the required production time from Table 4-38 and an operating year of 280 days (212 days ÷ 280 days/year x 12 months/yr = 9.1 months). Thus, the monthly wastewater release was 78.9 ccf (537,000 gallons ÷ 9.1 months ÷ 748 gal/ccf). To calculate the wastewater cost for the non-conveyorized nickel/gold process, the tiered cost scale was applied to the quantity of discharge, and the resulting costs per tier were summed, as follows:

$6.85 x 2 ccf/month = $13.70 ccf/month
$3.06 x 8 ccf/month = $24.48 ccf/month
$2.72 x 68.9 ccf/month = $187.40 ccf/month

Monthly discharge cost = $13.70 + $24.48 + $187.40 = $226/month

The monthly cost was then multiplied by the number of months required to produce 260,000 ssf of PWB to calculate the overall wastewater treatment cost:

WW = $226/month x 9.1 month = $2,050

Production Costs

Production Cost Calculation Methods. Production costs for the surface finishing process include both the cost of labor required to operate the process and the cost of transporting chemicals to the production line from storage. Production costs (P) were calculated by the following equation:

$$P = LA + TR$$

where,
LA   =   production labor cost ($/ssf) to produce 260,000 ssf
TR   =   chemical transportation cost ($/ssf) to produce 260,000 ssf

Production labor cost is a function of the number and type of employees and the length of time required to complete a job. The calculation of production labor cost assumes that line operators perform all of the daily activities, excluding bath maintenance, vital to the operation of the surface finishing process. Labor costs associated with bath maintenance activities, such as sampling and analysis, are presented in the discussion of maintenance costs, below. An average number of line operators was determined for conveyorized (one line operator) from PWB Workplace Practices Questionnaire data and site visit observations. Although no significant difference in the number of line operators by automation type was reported in the data, the number of line operators for non-conveyorized processes was adjusted upward to 1.1 to reflect the greater level of labor content for these processes, as compared to conveyorized processes.

The labor time required to complete the specified job was calculated assuming an average shift time of eight hours per day, and using the number of days required to produce 260,000 ssf of PWB from simulation results. A labor wage of $10.24/hr was obtained from the American Wages and Salary Survey (Fisher, 1999) and utilized for surface finishing line operators. Therefore, labor costs for process alternatives were calculated as follows:

LA = number of operators x $10.24/hr x 8 hr/day x required production time (days)

The production cost category of chemical transportation cost includes the cost of transporting chemicals from storage to the process line. A BOA, presented in Appendix G, was developed and used to calculate the unit cost per chemical transport. Because chemicals are consumed whenever a bath is replaced, the number of trips required to supply the process line with chemicals equals the number of bath replacements required to produce 260,000 ssf of PWB. Chemical transportation cost was calculated as follows:

TR = number of bath replacements x unit cost per chemical transport ($)

Example Production Cost Calculations. For the example of the non-conveyorized nickel/gold, production labor cost was calculated assuming 1.1 operators working for 212 days (see Table 4-38). Chemical transportation cost was calculated based on a cost per chemical transport of $9.28 (see Table 4-40 and Appendix G) and 72 bath replacements (see Table 4-37). Thus, the production cost was calculated as follows:

LA = 1.1 x $10.24 x 8 hr/day x 212 days = $19,100
TR = 72 x $9.28 = $668

thus,
P = $19,100 + $668 = $19,768

Maintenance Costs

Maintenance Cost Calculation Method. The maintenance costs for the surface finishing process include the costs associated with tank cleaning, bath setup, sampling and analysis of bath chemistries, and bath filter replacement. Maintenance costs were calculated as follows:

$$MA = TC + BS + FR + ST$$

where,
TC = tank cleanup cost ($/ssf) to produce 260,000 ssf
BS = bath setup cost ($/ssf) to produce 260,000 ssf
FR = filter replacement cost ($/ssf) to produce 260,000 ssf
ST = sampling cost ($/ssf) to produce 260,000 ssf

The maintenance costs listed above depend on the unit cost per repetition of the activity and the number of times the activity was performed. For each maintenance cost category, a BOA was developed to characterize the cost of labor, materials, and tools associated with a single repetition of that activity. The BOA and unit cost per repetition for each cost category are presented in Appendix G. It was assumed that the activities and costs characterized on the BOAs are the same, regardless of the surface finishing process or process baths. Unit costs per repetition for both tank cleanup and bath setup were determined to be $67.00 and $15.10, respectively.

The number of tank cleanups and bath setups equals the number of bath replacements obtained from process simulation results (see Appendix G). Each time a bath is replaced, the tank is cleaned before a replacement bath is created. The costs of tank cleanup and bath setup are thus given by the following:

$$TC = \text{number of tank cleanups x } \$67.00$$
$$BS = \text{number of bath setups x } \$15.10$$

The PWB Workplace Practices Questionnaire data for both filter replacement and bath sampling and analysis were reported in occurrences per year, instead of as a function of throughput, and are represented in Section 3.2, the Exposure Assessment. These frequencies were adjusted for this analysis using the URs for the production time required to manufacture 260,000 ssf of PWB. Using the unit costs determined by the BOAs developed for filter replacement ($17.50 per replacement), and bath sampling and testing ($3.70 per test), the costs for these maintenance activities were calculated as follows:

$$ST = \text{annual number of sampling \& testing x UR x } \$3.70$$
$$FR = \text{annual number of filter replacement x UR x } \$17.50$$

The total maintenance cost for each process alternative was determined by first calculating the individual bath maintenance costs using the above equations and then summing the results for all baths in that process.

Maintenance Costs Example Calculations. This section presents example maintenance costs calculations for the non-conveyorized nickel/gold process. From Table 4-38, this process has a production time of 212 days, which gives a UR of 0.76 (UR = 212 ÷ 280). The number of tank cleanups and bath setups equals the number of bath replacements reported in Table 4-37 (72 bath replacements). As reported in Section 3.2, Exposure Assessment, chemical baths are sampled and tested 1,260 times per year, and filters are replaced 119 times per year. Thus, the maintenance costs for the non-conveyorized nickel/gold process are:

$$TC = 72 \text{ x } \$67.00 = \$4,820$$
$$BS = 72 \text{ x } \$15.10 = \$1,090$$
$$ST = 1,260 \text{ x } 0.76 \text{ x } \$3.70 = \$3,530$$
$$FR = 119 \text{ x } 0.76 \text{ x } \$17.50 = \$1,580$$

Therefore, the overall maintenance cost for the process is:

$$MA = \$4,820 + \$1,090 + \$3,530 + \$1,580 = \$11,000$$

Determination of Total Cost and Unit Cost

The total cost for surface finishing process alternatives was calculated by summing the totals of the individual costs categories. The cost per ssf of PWB produced, or unit cost (UC), can then be calculated by dividing the total cost by the amount of PWBs produced. Table 4-44 summarizes the total cost of manufacturing 260,000 ssf of PWB using the non-conveyorized nickel/gold process.

The UC for the non-conveyorized nickel/gold process was calculated as follows:

$$
\begin{aligned}
UC &= \text{total cost (TC)} \div 260,000 \text{ ssf} \\
&= \$156,000 \div 260,000 \text{ ssf} \\
&= \$0.60/\text{ssf}
\end{aligned}
$$

Table 4-44. Summary of Costs for the Non-Conveyorized Nickel/Gold Process

Cost Category	Component	Component Cost [a]	Totals [a]
Capital Cost	Primary Equipment & Installation	$7,260	
	Facility	$2,930	**$10,200**
Material Cost	Chemical(s)	$109,000	**$109,000**
Utility Cost	Water	$1,180	
	Electricity	$2,360	
	Natural Gas	$0	**$3,540**
Wastewater Cost	Wastewater Discharge	$2,050	**$2,050**
Production Cost	Transportation of Material	$668	
	Labor for Line Operation	$19,100	**$19,800**
Maintenance Cost	Tank Cleanup	$4,820	
	Bath Setup	$1,090	
	Sampling and Analysis	$3,530	
	Filter Replacement	$1,580	**$11,000**
Total Cost			**$156,000**

[a] Costs of producing 260,000 ssf of PWB by the process.

4.2.6   Results

Table 4-45 presents the costs for each of the surface finishing technologies. Table 4-46 presents unit costs ($/ssf). The total cost of producing 260,000 ssf ranged from a low of $26,300 for the conveyorized OSP process to a high of $399,000 for the non-conveyorized nickel/palladium/gold process, with the corresponding unit costs ranging from $0.10/ssf to $1.54/ssf for the same two processes. With the exception of the two technologies containing gold, all of the other surface finishing alternatives were less expensive than the baseline, non-conveyorized HASL process.

Total cost data in Table 4-45 illustrate that chemical cost is the largest cost for all of the surface finishing processes. Labor costs were the second largest cost component, though far smaller than the cost of process chemicals.

Table 4-45. Total Cost of Surface Finishing Technologies

Cost Category	Cost Components	HASL, NC	HASL, C	Nickel/Gold, NC
Capital Cost	Primary Equipment & Installation	$9,360	$11,000	$7,260
	Facility	$432	$398	$2,930
Material Cost	Chemical(s)	$74,800	$75,200	$109,000
Utility Cost	Water	$706	$565	$1,180
	Electricity	$669	$452	$2,360
	Natural Gas	$88	$45	$0
Wastewater Cost	Wastewater Discharge	$1,100	$851	$2,050
Production Cost	Transportation of Material	$167	$130	$668
	Labor for Normal Production	$3,940	$1,790	$19,100
Maintenance Cost	Tank Cleanup	$1,210	$938	$4,820
	Bath Setup	$272	$211	$1,090
	Sampling and Testing	$499	$249	$3,530
	Filter Replacement	$967	$482	$1,580
Total Cost		**$94,200**	**$92,400**	**$156,000**

Table 4-45. Total Cost of Surface Finishing Technologies (cont.)

Cost Category	Cost Components	Nickel/Palladium/Gold, NC	OSP, NC	OSP, C
Capital Cost	Primary Equipment & Installation	$15,400	$1,640	$2,880
	Facility	$6,090	$320	$264
Material Cost	Chemical(s)	$321,000	$18,500	$18,800
Utility Cost	Water	$2,060	$441	$301
	Electricity	$4,050	$313	$208
	Natural Gas	$0	$66	$31
Wastewater Cost	Wastewater Discharge	$3,530	$702	$463
Production Cost	Transportation of Material	$1,030	$159	$121
	Labor for Normal Production	$25,200	$3,170	$1,320
Maintenance Cost	Tank Cleanup	$7,430	$1,140	$871
	Bath Setup	$1,680	$257	$196
	Sampling and Testing	$8,900	$1,610	$738
	Filter Replacement	$2,840	$330	$151
Total Cost		**$399,000**	**$28,700**	**$26,300**

Table 4-45. Total Cost of Surface Finishing Technologies (cont.)

Cost Category	Cost Components	Immersion Silver, C	Immersion Tin, NC	Immersion Tin, C
Capital Cost	Primary Equipment & Installation	$10,540	$2,950	$16,800
	Facility	$937	$892	$2,340
Material Cost	Chemical(s)	$52,700	$29,000	$28,900
Utility Cost	Water	$301	$1,030	$702
	Electricity	$739	$494	$1,230
	Natural Gas	$140	$162	$240
Wastewater Cost	Wastewater Discharge	$529	$1,620	$1,220
Production Cost	Transportation of Material	$167	$204	$167
	Labor for Normal Production	$5,260	$6,780	$8,770
Maintenance Cost	Tank Cleanup	$1,210	$1,470	$1,210
	Bath Setup	$272	$332	$272
	Sampling and Testing	$937	$1,260	$1,800
	Filter Replacement	$80	$705	$1,000
Total Cost		**$73,800**	**$46,900**	**$64,700**

Table 4-46. Surface Finishing Alternative Unit Costs for Producing 260,000 ssf of PWB

Surface Finishing Alternative	Total Cost ($)	Unit Cost ($/ssf)	Cost Savings [a] (%)
HASL, Non-conveyorized	94,200	0.36	---
HASL, Conveyorized	92,400	0.35	3
Nickel/Gold, Non-conveyorized	156,000	0.60	-67
Nickel/Palladium/Gold, Non-conveyorized	399,000	1.54	-327
OSP, Non-conveyorized	28,700	0.11	69
OSP, Conveyorized	26,300	0.10	72
Immersion Silver, Conveyorized	73,800	0.28	22
Immersion Tin, Non-conveyorized	46,900	0.18	50
Immersion Tin, Conveyorized	64,700	0.25	31

[a] Cost savings measured by comparing cost of the surface finish to the cost of the baseline non-conveyorized HASL process. Positive results represent percent savings from the costs incurred had the baseline process been used, while negative results represent percent lost.

4.2.7   Conclusions

This analysis generated comparative costs for six surface finishing technologies, including HASL, nickel/gold, nickel/palladium/gold, OSP, immersion silver, and immersion tin processes. Costs were developed for each technology and equipment configuration for which data were available from the PWB Workplace Practices Questionnaire and Performance Demonstration, for a total of nine processes (five non-conveyorized processes and four conveyorized processes). Costs were estimated using a hybrid cost model that combines traditional costs with simulation modeling and activity-based costs. The cost model was designed to determine the total cost of processing a specific amount of PWBs through a fully operational surface finishing line, in this case 260,000 ssf. The cost model does not estimate start-up costs for a facility switching to a surface finishing alternative, which could factor significantly in the decision to implement a technology. Total costs were divided by the throughput (260,000 ssf) to determine a unit cost in $/ssf.

The cost components considered include capital costs (primary equipment and installation, and facility costs), materials costs (limited to chemical costs), utility costs (water, electricity, and natural gas costs), wastewater costs (limited to wastewater discharge cost), production costs (production labor and chemical transport costs), and maintenance costs (tank cleanup, bath setup, sampling and analysis, and filter replacement costs). Other cost components may contribute significantly to overall costs, but were not quantified because they could not be reliably estimated. These include wastewater treatment cost, sludge recycling and disposal cost, other solid waste disposal costs, and quality costs.

Overall, the costs ranged from $0.10/ssf for the conveyorized OSP process to $1.54/ssf for the non-conveyorized nickel/palladium/gold process. The cost of the baseline non-conveyorized HASL process was calculated to be $0.36/ssf.

Based on the results of this analysis, six of the eight alternative surface finishing processes are more economical than the baseline non-conveyorized HASL process. Three processes had a substantial cost savings of at least 50 percent of the cost per ssf over that of the baseline HASL process (conveyorized OSP at 72 percent cost savings, non-conveyorized OSP at 69 percent, and non-conveyorized immersion tin at 50 percent). Three other process alternatives realized a somewhat smaller cost savings over the baseline HASL process (conveyorized immersion tin at 31 percent, conveyorized immersion silver at 22 percent, and the conveyorized HASL process at 3 percent.)

Two processes were more expensive than the baseline. The exceptions were the electroless nickel/immersion gold process and the electroless nickel/palladium/immersion gold process, both of which had chemical costs exceeding the *entire* cost of the non-conveyorized HASL process, due to the precious metal content of the surface finish.

In general, conveyorized processes cost less than non-conveyorized processes of the same technology due to the cost savings associated with their higher throughput rates. The exception to this was immersion tin, which was more costly because the combination of process cycle time and conveyor length resulted in a lower throughput rate than its non-conveyorized version.

Chemical cost was the single largest component cost for all of the nine processes. Labor costs were the second largest cost component, though far smaller than the cost of process chemicals.

4.3   REGULATORY ASSESSMENT

This section describes the federal environmental regulations that may affect the use of chemicals in the surface finishing processes during PWB manufacturing. Discharges of these chemicals may be restricted by air, water, or solid waste regulations, and releases may be reportable under the federal Toxic Release Inventory (TRI) program. This section discusses and illustrates pertinent portions of federal environmental regulations that may be pertinent to surface finishing operations, including the Clean Water Act (Table 4-47), the Clean Air Act (Table 4-53), the Resource Conservation and Recovery Act, the Comprehensive Environmental Response, Compensation, and Liability Act (Table 4-54), the Superfund Amendments and Reauthorization Act and Emergency Planning and Community Right-To-Know Act (Table 4-55), and the Toxic Substances Control Act (Table 4-56). This section is intended to provide an overview of environmental regulations triggered by the use of the identified chemicals; it is not intended to be used as regulatory guidance.

The primary sources of information for this section were the EPA Register of Lists (U.S. EPA, 1998) and the EPA document, "Federal Environmental Regulations Affecting the Electronics Industry" (U.S. EPA, 1995). The former is a database of federal regulations applicable to specific chemicals that can be searched by chemical. The latter was prepared by the DfE PWB Project. Of the 83 chemicals reportedly used in one or more of the evaluated surface finishing technologies, no regulatory listings were found for 40 chemicals.

4.3.1   Clean Water Act

The Clean Water Act (CWA) is the basic federal law governing water pollution control in the U.S. today. The various surface finishing processes used by the PWB industry produce a number of pollutants that are regulated under the CWA. Applicable provisions, as related to specific chemicals, are presented in Table 4-47; these particular provisions and process-based regulations are discussed in greater detail below.

CWA Hazardous Substances and Reportable Quantities

Under Section 311(b)(2)(A) of the CWA, the Administrator designates hazardous substances which, when discharged to navigable waters or adjoining shorelines, present an imminent and substantial danger to the public health or welfare, including fish, shellfish, wildlife, shorelines, and beaches. 40 Code of Federal Regulations (CFR) Part 117 establishes the Reportable Quantity (RQ) for each substance listed in 40 CFR Part 116. When an amount equal to or in excess of the RQ is discharged, the facility must provide notice to the federal government of the discharge, following Department of Transportation requirements set forth in 33 CFR Section 153.203. Liability for cleanup can result from such discharges. This requirement does not apply to facilities that discharge the substance under a National Pollutant Discharge Elimination System (NPDES) Permit or a CWA Section 404 dredge and fill permit, or to a publicly owned treatment works (POTW), as long as any applicable effluent limitations or pretreatment standards have been met. Table 4-47 lists RQs of hazardous substances under the CWA that may apply to chemicals used in the surface finishing process.

Table 4-47. CWA Regulations That May Apply to Chemicals in the Surface Finishing Process

Chemical [a]	CWA 311 RQ (lbs)	CWA Priority Pollutant	CWA 307a	CWA 304(b)
Acetic acid	5,000			
Ammonium hydroxide	1,000			
Copper ion		X	X	X
Copper sulfate pentahydrate		X	X	X
Ethylenediamine	5,000			
Hydrochloric acid	5,000			
Nickel sulfate	100	X	X	X
Nitric acid	1,000			
Phosphoric acid	5,000			
Propionic acid	5,000			
Silver nitrate	1	X	X	X
Sodium hydroxide	1,000			
Sulfuric acid	1,000			
Urea				

[a] In addition to the chemicals listed, there are 29 confidential business information (CBI) chemicals that would fall under CWA regulations.
Abbreviations and Definitions:
CWA - Clean Water Act
CWA 304(b) - Effluent Limitations Guidelines
CWA 307(a) - Toxic Pollutants Pretreatment Standards
CWA 311 - Hazardous Substances
RQ - Reportable Quantity

The NPDES permit program (40 CFR Part 122) contains regulations governing the discharge of pollutants to waters of the U.S. Forty-three states and one territory are authorized to administer NPDES programs that are at least as stringent as the federal program; EPA administers the program in states or territories that are not authorized to do so, and on Native American lands. The following discussion covers federal NPDES requirements. Facilities may be required to comply with additional state requirements not covered in this document.

The NPDES program requires permits for the discharge of "pollutants" from any "point source" into "navigable waters" (except those covered by Section 404 dredge and fill permits). The CWA defines all of these terms broadly, and a source is required to obtain an NPDES permit if it discharges almost anything other than dredge and fill material directly to surface water. A source that sends its wastewater to a POTW is not required to obtain an NPDES permit, but may be required to obtain an industrial user permit from the POTW to cover its discharge.

CWA Priority Pollutant

In addition to other NPDES permit application requirements, facilities need to be aware of priority pollutants listed in 40 CFR Part 122, Appendix D; this list of 126 compounds was developed by EPA to define a specific list of chemicals to be given priority consideration in the development of effluent limitation guidelines. Each PWB applicant for an NPDES permit must provide quantitative data for those priority pollutants that the applicant knows or has reason to believe, will be discharged in greater than trace amounts. Each applicant also must indicate if it knows, or has reason to believe, it discharges any of the other hazardous substances or non-conventional pollutants listed at 40 CFR Part 122, Appendix D. In some cases, quantitative testing is required for these pollutants; in other cases, the applicant must describe why it expects the pollutant to be discharged and provide the results of any quantitative data about its discharge for that pollutant.

CWA Effluent Limitation Guidelines [CWA 301(b), 304(b)]

A principal means for attaining water quality objectives under the CWA is the establishment and enforcement of technology-based effluent limitations, which are based on the pollutant control capabilities of available technologies, taking into consideration the economic achievability of these limitations and a number of other factors. Because of differences in production processes, quantities, and composition of discharges, separate national standards are established for discharges associated with different industry categories. These standards are referred to as technology-based effluent limitation guidelines.

The effluent limitation to be applied to a particular pollutant in a particular case depends on the following:

• whether the pollutant is conventional, non-conventional, or toxic;
• whether the point source is a new or existing source; and
• whether the point source discharges directly to the waters of the U.S. or to a POTW. (Facilities that discharge to POTWs must comply with the pretreatment standards.)

Existing sources must comply with either best practicable control technology currently available (BPT), best conventional pollution control technology (BCT), or best available control technology economically achievable (BAT) standards. New facilities must comply with New Source Performance Standards. NPDES permits also must contain any more stringent permit limitations based on state water quality standards.

In the absence of effluent limitation guidelines for a facility category, permit writers establish technology-based controls using their best professional judgement. In essence, the permit writer undertakes an effluent guideline-type analysis for a single facility. The permit writer will use information such as permit limits from similar facilities using similar treatment technology, performance data from actual operating facilities, and scientific literature. Best Professional Judgement may not be used in lieu of existing effluent guidelines. These guidelines apply only to direct dischargers of wastewater.

Pretreatment Standards

Only those facilities that discharge pollutants into waters of the U.S. need to obtain an NPDES permit. Facilities that discharge to POTWs, however, must comply with pretreatment requirements, as set out in Section 307(a) of CWA. These requirements were developed because of concern that dischargers' waste containing toxic, hazardous, or concentrated conventional industrial wastes might "pass through" POTWs, or that pollutants might interfere with the successful operation of the POTW. EPA has established national, technology-based "categorical pre-treatment standards" by facility category. In addition, or for industry categories without national standards, POTWs may establish "local limits" or individual industrial facilities.

Wastewater emission standards for the PWB industry can be found at 40 CFR Part 413 and 433, which include the Pretreatment Standards for Existing Sources (PSES) and Pretreatment Standards for New Sources (PSNS) that regulate PWB industry and wastewater, respectively. The major constituents of PWB wastewater are heavy metals and other cations.

The PSES and the PSNS establish maximum concentration levels of several metals that cannot be exceeded. They also regulate cyanide, which is used in some surface finishing alternatives. Generally speaking, PSNS puts more stringent regulations on pollutants than PSES. A summary of PSES for metals is included in Tables 4-48 and 4-49.

Table 4-48. Printed Circuit Board Facilities Discharging Less than 38,000 Liters per Day PSES Limitations (mg/L)

Pollutant or Pollutant Property	Max. Value for Any 1 Day (ppm)	Average Daily Values for 4 Consecutive Monitoring Days that Shall Not be Exceeded mg/L (ppm)
Cyanide (CN)	5.0	2.7
Lead (Pb)	0.6	0.4
Cadmium (Cd)	1.2	0.7

Table 4-49. Printed Circuit Board Facilities Discharging 38,000 Liters per Day or More PSES Limitations (mg/L)

Pollutant or Pollutant Property	Max. Value for Any 1 Day (ppm)	Average Daily Values for 4 Consecutive Monitoring Days that Shall Not be Exceeded mg/L (ppm)
Copper (Cu)	4.5	2.7
Nickel (Ni)	4.1	2.6
Lead (Pb)	0.6	0.4
Cadmium (Cd)	1.2	0.7
Silver (Ag)	1.2	0.7
Total Metals	10.5	6.8
Cyanide (CN)	1.9	1.0
PH	7.5 < pH < 10.0	7.5 < pH < 10.0

Both 40 CFR Part 433.17, PSNS, and Part 433.16, New Source Performance Standards (NSPS), have the same and more stringent regulated metal levels. Tables 4-50 and 4-51 summarize these sections.

Table 4-50. PSNS for Metal Finishing Facilities

Pollutant or Pollutant Property	Max. Value for Any 1 Day (ppm)	Average Daily Values for 4 Consecutive Monitoring Days that Shall Not be Exceeded mg/L (ppm)
Copper (Cu)	3.38	2.07
Nickel (Ni)	3.98	2.38
Lead (Pb)	0.69	0.43
Cadmium (Cd)	0.11	0.07
Silver (Ag)	0.43	0.24
Cyanide (CN)	1.20	0.65
PH	$6.0 < pH < 9.0$	$6.5 < pH < 9.0$

Table 4-51. Amenable Cyanide Limitation Upon Agreement

Pollutant or Pollutant Property	Max. Value for Any 1 Day (ppm)	Average Daily Values for 4 Consecutive Monitoring Days that Shall Not be Exceeded mg/L (ppm)
Cyanide (CN)	0.86	0.32

There is one table in 40 CFR Part 433.15 that shows a different set of PSES for all plants except job shops and independent printed circuit board manufacturers. Although most of the PWB companies participating in this project are independent manufacturers, Table 4-52 summarizes that section for reference purposes.

Table 4-52. PSES for All Plants Except Job Shops and Independent PWB Manufacturers

Pollutant or Pollutant Property	Max. Value for Any 1 Day (ppm)	Average Daily Values for 4 Consecutive Monitoring Days that Shall Not be Exceeded mg/L (ppm)
Copper (Cu)	3.38	2.07
Nickel (Ni)	3.98	2.38
Lead (Pb)	0.69	0.43
Cadmium (Cd)	0.69	0.26
Silver (Ag)	0.43	0.24
Cyanide (CN)	1.20	0.64

4.3.2   Clean Air Act

The Clean Air Act (CAA), with its 1990 amendments, sets the framework for air pollution control in the U.S. The various surface finishing processes produce a number of pollutants that are regulated under the CAA. Applicable provisions, as related to specific chemicals, are presented in Table 4-53; these particular provisions and process-based regulations are discussed below.

Table 4-53. CAA Regulations That May Apply to Chemicals in the Surface Finishing Process

Chemical [a]	CAA 111	CAA 112b	CAA 112r
Acetic acid	X		
Ethylene glycol	X	X	
Ethylenediamine	X		X
Hydrochloric acid		X	X
Malic acid	X		
Nickel sulfate		X	
Propionic acid	X		
Sulfuric acid	X		

[a] In addition to the chemicals listed, there are 16 CBI chemicals that have been identified as falling under the CAA regulations discussed.
Abbreviations and Definitions:
CAA - Clean Air Act
CAA 111 - Standards of Performance for New Stationary Sources of Air Pollutants-Equipment Leaks Chemical List
CAA 112b - Hazardous Air Pollutant
CAA 112r - Risk Management Program

Hazardous Air Pollutants

Section 112 of the CAA established a regulatory program for 188 hazardous air pollutants and directed EPA to add other pollutants to the list, as needed. EPA is required to establish Maximum Achievable Control Technology (MACT) standards for source categories that emit at least one of the pollutants on the list in major quantities. Chemicals listed in Section 112 (b) of the CAA that are used in surface finishing are shown in Table 4-53. EPA has identified categories of industrial facilities that emit substantial quantities of any of these 188 pollutants and plan to develop emissions limits for those industry categories between 1992 and 2000.

Section 112(r) of the CAA deals with sudden releases of, or accidents involving acutely toxic, explosive, or flammable chemicals. This provision, added by the CAA Amendments of 1990, establishes a list of substances which, if present in a process in a quantity exceeding a threshold, would require the facility to establish a Risk Management Program to prevent chemical accidents. This program must include preparation of a risk management plan, which is submitted to the state and local emergency planning organizations.

Minimum Standards for State Operating Permit Programs

The CAA and its implementing regulations (at 40 CFR Part 70) define the minimum standards and procedures required for state operating permit programs. The permit system is a new approach established by the 1990 Amendments that is designed to define each source's requirements and to facilitate enforcement. In addition, permit fees generate revenue to fund the program's implementation.

Any facility defined as a "major source" is required to secure a permit. Section 70.2 of the regulations defines a major source, in part, based upon if the source emits or has the potential to emit:

- 10 tons per year (TPY) or more of any hazardous air pollutant;
- 25 TPY or more of any combination of hazardous air pollutants; or
- 100 TPY of any air pollutant.

For ozone non-attainment areas, major sources are defined as sources with the potential to emit:

- 100 TPY or more of volatile organic compounds (VOCs) or oxides of nitrogen (NOx) in areas classified as marginal or moderate;
- 50 TPY or more of VOCs or NOx in areas classified as serious;
- 25 TPY or more of VOCs or NOx in areas classified as severe; and
- 10 TPY or more of VOCs or NOx in areas classified as extreme.

Section 70.2 also defines certain other major sources in ozone transport regions and serious non-attainment areas for carbon monoxide and particulate matter. In addition to major sources, all sources that are required to undergo New Source Review, sources that are subject to New Source Performance Standards or section 112 air toxics standards, and any affected source, must obtain a permit.

By November 15, 1993, each state was required to submit an operating permit program to EPA for approval. EPA was required to either approve or disapprove the state's program within one year after submission. Once approved, the state program went into effect.

Major sources, as well as other sources identified above, were to submit their permit applications to the state within one year of approval of the state program. Once a source submits a timely and complete application, it may continue to operate until the permit is issued. Permit issuance may take years because permit processing allows time for terms and conditions to be reviewed by the public and neighboring states as well as by EPA.

When issued, the permit includes all federal air requirements applicable to the facility, such as compliance schedules, emissions monitoring, emergency provisions, self-reporting responsibilities, and emissions limitations. States may also choose to include state air requirements in the permit. Five years is the maximum permit term.

As established in 40 CFR Part 70, the states are required to develop fee schedules to ensure the collection and retention of revenues sufficient to cover permit program costs. The CAA has set a presumptive minimum annual fee of $25 per ton for all regulated pollutants (except carbon monoxide), indexed for inflation, but states may set higher or lower fees as long as they collect sufficient revenues to cover program costs.

4.3.3   Resource Conservation and Recovery Act

One purpose of the Resource Conservation and Recovery Act (RCRA) of 1976 (as amended in 1984) is to set up a cradle-to-grave system for tracking and regulating hazardous waste. EPA has issued regulations, found in 40 CFR Parts 260-299, which implement the federal statute. These regulations are Federal requirements. Currently, 47 states have been authorized to implement the basic RCRA program and may include more stringent requirements in their authorized RCRA programs. In addition, non-RCRA-authorized states (Alaska, Hawaii, and Iowa) may have state laws establishing hazardous waste management requirements. A facility always should check with its state when analyzing which requirements apply to its activities.

To be an RCRA "hazardous waste", a material must first be a solid waste, which is defined broadly under RCRA and RCRA regulations. Assuming the material is a solid waste, the first evaluation to be made is whether or not it is also considered a hazardous waste. 40 CFR Part 261 addresses the identification and listing of hazardous waste. Waste generators are responsible for determining whether a waste is hazardous, and what classification, if any, may apply to the waste. Generators must undertake testing, or use their own knowledge and familiarity with the waste, to determine if it is hazardous. Generators may be subject to enforcement penalties for improperly determining that a waste is not hazardous.

RCRA Hazardous Waste Codes

Wastes can be classified as hazardous either because they are listed by EPA through regulation in 40 CFR Part 261, or because they exhibit certain characteristics; namely toxicity, corrosivity, reactivity, and ignitability. Listed hazardous wastes are specifically named (e.g., discarded commercial toluene, spent non-halogenated solvents). Characteristic hazardous wastes are solid waste which "fail" a characteristic test, such as the RCRA test for ignitability.

There are four separate lists of hazardous wastes in 40 CFR Part 261. If any waste from a PWB facility is on any of these lists, the facility is subject to regulation under RCRA (there are two CBI chemicals used in a surface finishing process that have been identified as "U" listed wastes). The listing is often defined by industrial processes, but all wastes are listed because they were determined to be hazardous (these hazardous constituents are listed in Appendix VII to Part 261). Section 261.31 lists wastes from non-specific sources and includes wastes generated by industrial processes that may occur in several different industries; the codes for such wastes always begin with the letter "F." The second category of listed wastes (40 CFR Section 261.32) includes hazardous wastes from specific sources; these wastes have codes that begin with the letter "K." The remaining lists (40 CFR Section 261.33) cover commercial chemical products that have been or are intended to be discarded; these have two letter designations, "P" and "U."

Waste codes beginning with "P" are considered acutely hazardous, while those beginning with "U" are simply considered hazardous.

Generator Status

A hazardous waste generator is defined as any person, by site, who creates a hazardous waste or makes a waste subject to RCRA Subtitle C. Generators are divided into three categories:

1. Large Quantity Generators — facilities that generate at least 1,000 kg (approximately 2,200 lbs) of hazardous waste per month, or greater than 1 kg (2.2 lbs) of acutely hazardous waste per month.
2. Small Quantity Generators — facilities that generate greater than 100 kg (approximately 220 lbs) but less than 1,000 kg of hazardous waste per month, and up to 1 kg (2.2 lbs) per month of acutely hazardous waste.
3. Conditionally Exempt Small Quantity Generators — facilities that generate no more than 100 kg (approximately 220 lbs) per month of hazardous waste and up to 1 kg (2.2 lbs) per month of acutely hazardous waste.

Large and small quantity generators must meet many similar requirements. 40 CFR Part 262 provides that small quality generators may accumulate up to 6,000 kg of hazardous waste on-site, at any one time, for up to 180 days without being regulated as a treatment, storage, or disposal facility (TSDF), which requires a TSDF permit. The provisions of 40 CFR 262.34(f) allow small quality generators to accumulate waste on-site for 270 days without having to apply for TSDF status, provided the waste must be transported over 200 miles. Large quantity generators have only a 90-day window to ship wastes off-site without needing a RCRA TSDF permit. Keep in mind that most provisions of 40 CFR Parts 264 and 265 (for hazardous waste treatment, storage and disposal facilities) do not apply to generators who send their wastes off-site within the 90- or 180-day window, whichever is applicable.

Hazardous waste generators that do not meet the conditions for being conditionally exempt, small quantity generators must (among other requirements such as record keeping and reporting):

*   obtain a generator identification number;
*   accumulate and ship hazardous waste in suitable containers or tanks (for accumulation only);
*   manifest the waste properly;
*   maintain copies of the manifest, a shipment log covering all hazardous waste shipments, and test records;
*   comply with applicable land disposal restriction requirements; and
*   report releases or threats of releases of hazardous waste.

TSDF Status

As mentioned above, Subtitle C of RCRA (40 CFR Parts 264 and 265) establishes substantive permit requirements for facilities that treat, store, or dispose of hazardous wastes. Generators (unless exempt, e.g., through the conditionally exempt, small quantity generators exemption [see 40 CFR Part 261.5(g)]), no matter what monthly waste output, with waste on site, for more than 90 days are classified as TSDFs. TSDFs must comply with 40 CFR Part 264-267 and Part 270, including permit requirements and stringent technical and financial responsibility requirements. Generators who discharge hazardous waste into a POTW, or from a point source regulated by an NPDES permit, are not required to comply with TSDF regulations.

4.3.4   Comprehensive Environmental Response, Compensation and Liability Act

The Comprehensive Environmental Response, Compensation and Liability Act (also known as CERCLA, or more commonly as "Superfund") was enacted in 1980. CERCLA is the Act that created the Superfund hazardous substance cleanup program and set up a variety of mechanisms to address risks to public health, welfare, and the environment caused by hazardous substance releases.

CERCLA RQs

Substances defined as hazardous under CERCLA are listed in 40 CFR Section 302.4. Under CERCLA, EPA has assigned a RQ to most hazardous substances; regulatory RQs are either 1, 10, 100, 1,000, or 5,000 pounds (except for radionuclides). If EPA has not assigned a regulatory RQ to a hazardous substance, typically its RQ is one pound (Section 102). Any person in charge of a facility (or vessel) must immediately notify the National Response Center as soon as a person has knowledge of a hazardous substance release in an amount that is equal to or greater than its RQ. There are some exceptions to this requirement, including the exceptions for federally permitted releases. There is also streamlined reporting for certain continuous releases (see 40 CFR 302.8). Table 4-54 lists RQs of substances under CERCLA that may apply to chemicals used in surface finishing processes.

Table 4-54. CERCLA RQs That May Apply to Chemicals in the Surface Finishing Process

Chemical [a]	CERCLA RQ (lbs)	Chemical [a]	CERCLA RQ (lbs)
Acetic acid	5,000	Phosphoric acid	5,000
Ammonium hydroxide	1,000	Propionic acid	5,000
Copper ion	1	Silver nitrate	1
Ethylene glycol	5,000	Sodium hydroxide	1,000
Ethylenediamine	5,000	Sulfuric acid	1,000
Hydrochloric acid	5,000	Thiourea	10
Nickel sulfate	100		

[a] In addition to the chemicals listed, there are 17 CBI chemicals with reportable quantities under CERCLA.
Abbreviations and Definitions:
CERCLA - Comprehensive Environmental Response, Compensation and Liability Act
RQ - Reportable Quantity

CERCLA Liability

CERCLA further makes a broad class of parties liable for the costs of removal or remediation of the release, or threatened release, of any hazardous substance at a facility. Section 107 specifies the parties liable for response costs, including the following: 1) current owners and operators of the facility; 2) owners and operators of a facility at the time hazardous substances were disposed; 3) persons who arranged for disposal, treatment, or transportation for disposal or treatment of such substances; and 4) persons who accepted such substances for transportation for disposal or treatment. These parties are liable for: 1) all costs of removal or remedial action incurred by the federal government, a state, or an Indian tribe not inconsistent with the National Contingency Plan (NCP); 2) any other necessary costs of response incurred by any person consistent with the NCP; 3) damages for injury to natural resources; and d) costs of health assessments.

4.3.5   Superfund Amendments and Reauthorization Act and Emergency Planning and Community Right-To-Know Act

CERCLA was amended in 1986 by the Superfund Amendments and Reauthorization Act (SARA). Title III of SARA is also known as the Emergency Planning and Community Right-To-Know Act (EPCRA). Certain sections of SARA and EPCRA may be applicable to surface finishing chemicals and PWB manufacturers. Table 4-55 lists applicable provisions as related to specific chemicals.

SARA Priority Contaminants

SARA Section 110 addresses Superfund site priority contaminants. This list contains the 275 highest-ranking substances of the approximately 700 prioritized substances. These chemical substances, found at Superfund sites, are prioritized based on their frequency of occurrence, toxicity rating, and potential human exposure. Once a substance has been listed, the Agency for Toxic Substances and Disease Registry must develop a toxicological profile containing general health/hazard assessments with effect levels, potential exposures, uses, regulatory actions, and further research needs.

EPCRA Extremely Hazardous Substances

Section 302(a) of EPCRA regulates extremely hazardous substances and is intended to facilitate emergency planning for response to sudden toxic chemical releases. Facilities must notify the State Emergency Response Commission (SERC) if these chemicals are present in quantities greater than their threshold planning quantities. These same substances also are subject to regulation under EPCRA Section 304, which requires accidental releases in excess of reportable quantities to be reported to the SERC and Local Emergency Planning Committee.

EPCRA Toxic Release Inventory

Under EPCRA Section 313, a facility in a covered Standard Industrial Code (SIC), that has 10 or more full-time employees, or the equivalent, and that manufactures, processes, or otherwise uses a toxic chemical listed in 40 CFR Section 372.65 above the applicable reporting threshold, must either file a toxic chemical release inventory reporting form (EPA Form R) covering release and other waste management activities, or if applicable, an annual certification statement (EPA Form A). The activity thresholds are 25,000 pounds per year for manufacturing (including importing) and processing, and 10,000 pounds per year for the otherwise use of a listed toxic chemical. Facilities that do not manufacture, process, or otherwise use more than one million pounds of a toxic chemical, and have a total annual reportable amount of no greater than 500 pounds for the chemical, may utilize the briefer Form A certification statement. The Form R, or form A if applicable, must be filed with the EPA and a state agency where the facility is located. Beginning in the 1991 reporting year, facilities must also report pollution prevention and recycling data for TRI chemicals on Form R pursuant to Section 6607 of the Pollution Prevention Act, 42 U.S.C. 13106. Table 4-55 lists chemicals used in surface finishing processes that are listed in the TRI.

Table 4-55. SARA and EPCRA Regulations That May Apply to Chemicals in the Surface Finishing Process

Chemical [a]	SARA 110	EPCRA 302a	EPCRA 313
Ammonium hydroxide			X
Copper ion	X		X
Copper sulfate pentahydrate	X		X
Ethylene glycol			X
Ethylenediamine		X	
Nickel sulfate	X		X
Palladium chloride	X		
Phosphoric acid			X
Sulfuric acid		X	X

[a] In addition to the chemicals listed, there are 14 CBI chemicals identified as falling under the SARA and EPCRA regulations discussed.

Abbreviations and definitions:
SARA - Superfund Amendments and Reauthorization Act
SARA 110 - Superfund Site Priority Contaminant
EPCRA - Emergency Planning & Community Right-To-Know Act
EPCRA 302a - Extremely Hazardous Substances
EPCRA 313 - Toxic Chemical Release Inventory

4.3.6 Toxic Substances Control Act

The Toxic Substances Control Act (TSCA), 15 U.S.C. Sections 2601-2692 (Regulations found at 40 CFR part 700-799), originally passed in 1976 and subsequently amended, applies to the manufacturers, importers, processors, distributors, users, and disposers of chemical substances or mixtures. Table 4-56 lists TSCA regulations and testing lists that may be pertinent to surface finishing processes.

Table 4-56. TSCA Regulations and Lists That May Apply to Chemicals Used in Surface Finishing Processes

Chemical [a]	TSCA 8d HSDR	TSCA MTL	TSCA 8a PAIR
Ethylene glycol		X	
Palladium chloride			X

[a] In addition to the chemicals listed, there are 10 CBI chemicals identified as falling under the TSCA regulations discussed.
Definitions and abbreviations:
TSCA - Toxic Substances Control Act
TSCA 8d HSDR - Health & Safety Data Reporting Rules
TSCA MTL - Master Testing List
TSCA 8a PAIR - Preliminary Assessment Information Rule

Testing Requirements

Section 4 authorizes EPA to require the testing of any chemical substance or mixture for potential adverse health and environmental effects. On finding that such testing is necessary, due to insufficient data from which the chemical's effects can be predicted, and that either: 1) activities involving the chemical may present an unreasonable risk of injury to health or the environment; or 2) the chemical is produced in substantial quantities and enters the environment in substantial quantities, or there is significant or substantial human or environmental exposure to the chemical.

The TSCA Master Testing List (MTL) is a list compiled by the EPA Office of Pollution Prevention and Toxics to set the Agency's testing agenda. The major purposes are to: 1) identify chemical testing needs; 2) focus limited EPA resources on those chemicals with the highest priority testing needs; 3) publicize EPA's testing priorities for industrial chemicals; 4) obtain broad public comments on EPA's testing program and priorities; and 5) encourage initiatives by industry to help EPA meet those priority needs. The 1996 MTL now contains over 500 specific chemicals in 10 categories.

Unpublished Health and Safety Data Reporting Requirements

Under section 8(d) of TSCA, EPA has promulgated regulations that require that any person who manufactures, imports, or, in some cases, processes (or proposes to manufacture, import, or, in some cases, process) a chemical substance or mixture identified under 40 CFR part 716, must submit to EPA copies of unpublished health and safety studies with respect to that substance or mixture.

Preliminary Assessment Information Rule

Under section 8(a) of TSCA, EPA has promulgated regulations at 40 CFR part 712, Subpart B (the Preliminary Assessment Information Rule (PAIR), which establishes procedures for chemical manufacturers and importers to report production, use, and exposure-related information on listed chemical substances. Any person (except a small manufacturer or importer) who imports or manufactures chemicals identified by EPA in this rule, must report information on production volume, environmental releases, and certain other releases. Small manufacturers or importers may be required to report such information on certain chemicals.

4.3.7   Summary of Regulations for Surface Finishing Technologies

Tables 4-57 through 4-62 provide a summary of regulations that may apply to chemicals in each of the surface finishing technology categories.

Table 4-57. Summary of Regulations that May Apply to Chemicals Used in Hot Air Solder Leveling (HASL) Technology

Process Chemical	CWA				CAA			EPCRA		SARA	TSCA			RCRA Waste	
	304b	307a	311	Priority Poll.	111	112b	112r	313	302a	110	8d HSDR	MTL	8a PAIR	P	U
Copper sulfate pentahydrate	X	X		X				X		X					
Ethylene glycol					X	X		X				X			
Hydrochloric acid			X			X	X	X	X			X			
Hydrogen peroxide									X			X			
Phosphoric acid			X					X							
Sodium hydroxide			X												
Sulfuric acid			X		X				X						
CBI chemicals (13)					1	1		2			3	1	3		

Note: For technologies with more than one process submitted for evaluation (i.e., nickel/gold, OSP, immersion tin), the number of listed chemicals subject to regulation reflects the total number of chemicals for both processed.

Abbreviations and definitions:
CAA - Clean Air Act
CAA 111 - Standards of Performance for New Stationary Sources of Air Pollutants-Equipment Leaks Chemical List
CAA 112b - Hazardous Air Pollutant
CAA 112r - Risk Management Program
CWA - Clean Water Act
CWA 304b - Effluent Limitations Guidelines
CWA 307a - Toxic Pollutants
CWA 311 - Hazardous Substances
CWA Priority Pollutants
EPCRA - Emergency Planning and Community Right-to-Know Act
EPCRA 302a - Extremely Hazardous Substances
EPCRA 313 - Toxic Chemical Release Inventory

RCRA - Resource Conservation and Recovery Act
RCRA P Waste - Listed acutely hazardous waste
RCRA U Waste - Listed hazardous waste
SARA - Superfund Amendments and Reauthorization Act
SARA 110 - Superfund Site Priority Contaminant
TSCA - Toxic Substances Control Act
TSCA 8d HSDR - Health & safety data reporting rules
TSCA MTL - Master Testing List
TSCA 8a PAIR - Preliminary Assessment Information Rule

Table 4-58. Summary of Regulations that May Apply to Chemicals Used in Nickel/Gold Technology

Process Chemical	CWA				CAA			SARA	EPCRA		TSCA			RCRA Waste	
Chemicals Subject to Applicable Regulation															
	304b	307a	311	Priority Poll.	111	112b	112r	110	313	302a	8d HSDR	MTL	8a PAIR	P	U
Ammonium hydroxide			X						X						
Copper sulfate pentahydrate	X	X		X				X	X						
Hydrochloric acid			X			X	X		X	X		X			
Hydrogen peroxide										X		X			
Malic acid					X										
Nickel sulfate	X	X	X	X		X		X	X						
Palladium chloride								X					X		
Phosphoric acid			X						X						
Sodium hydroxide			X												
Sulfuric acid			X		X					X					
CBI Chemicals (19)	4	4	10	4	9	4		4	7		1	2	2		

Note: For technologies with more than one process submitted for evaluation (i.e., nickel/gold, OSP, immersion tin), the number of listed chemicals subject to regulation reflects the total number of chemicals for both processed.

Abbreviations and definitions:
CAA - Clean Air Act
CAA 111 - Standards of Performance for New Stationary Sources of
Air Pollutants-Equipment Leaks Chemical List
CAA 112b - Hazardous Air Pollutant
CAA 112r - Risk Management Program
CWA - Clean Water Act
CWA 304b - Effluent Limitations Guidelines
CWA 307a - Toxic Pollutants
CWA 311 - Hazardous Substances
CWA Priority Pollutants
EPCRA - Emergency Planning and Community Right-to-Know Act
EPCRA 302a - Extremely Hazardous Substances
EPCRA 313 - Toxic Chemical Release Inventory
RCRA - Resource Conservation and Recovery Act

RCRA P Waste - Listed acutely hazardous waste
RCRA U Waste - Listed hazardous waste
SARA - Superfund Amendments and Reauthorization Act
SARA 110 - Superfund Site Priority Contaminant
TSCA - Toxic Substances Control Act
TSCA 8d HSDR - Health & safety data reporting rules
TSCA MTL - Master Testing List
TSCA 8a PAIR - Preliminary Assessment Information Rule

Table 4-59. Summary of Regulations that May Apply to Chemicals Used in Nickel/Palladium/Gold Technology

Process Chemical	CWA				CAA			SARA	EPCRA		TSCA			RCRA Waste	
	304b	307a	311	Priority Poll.	111	112b	112r	110	313	302a	8d HSDR	MTL	8a PAIR	P	U
Ammonium hydroxide			X						X						
Copper sulfate pentahydrate	X	X		X				X	X						
Ethylenediamine															
Hydrochloric acid			X			X	X		X	X		X			
Hydrogen peroxide									X			X			
Nickel sulfate	X	X	X	X		X		X	X						
Palladium chloride									X				X		
Phosphoric acid			X						X						
Propionic acid															
Sodium chloride															
Sodium hydroxide			X												
Sulfuric acid			X		X				X						
CBI Chemicals (20)	3	3	6	3	4	3		3	5		1	2	3		

Note: For technologies with more than one process submitted for evaluation (i.e., nickel/gold, OSP, immersion tin), the number of listed chemicals subject to regulation reflects the total number of chemicals for both processed.

Abbreviations and definitions:
CAA - Clean Air Act
CAA 111 - Standards of Performance for New Stationary Sources of Air Pollutants-Equipment Leaks Chemical List
CAA 112b - Hazardous Air Pollutant
CAA 112r - Risk Management Program
CWA - Clean Water Act
CWA 304b - Effluent Limitations Guidelines
CWA 307a - Toxic Pollutants
CWA 311 - Hazardous Substances
CWA Priority Pollutants
EPCRA - Emergency Planning and Community Right-to-Know Act
EPCRA 302a - Extremely Hazardous Substances

EPCRA 313 - Toxic Chemical Release Inventory
RCRA - Resource Conservation and Recovery Act
RCRA P Waste - Listed acutely hazardous waste
RCRA U Waste - Listed hazardous waste
SARA - Superfund Amendments and Reauthorization Act
SARA 110 - Superfund Site Priority Contaminant
TSCA - Toxic Substances Control Act
TSCA 8d HSDR - Health & safety data reporting rules
TSCA MTL - Master Testing List
TSCA 8a PAIR - Preliminary Assessment Information Rule

Table 4-60. Summary of Regulations that May Apply to Chemicals Used in OSP Technology

Process Chemical	CWA				CAA			SARA	EPCRA		TSCA			RCRA Waste	
Chemicals Subject to Applicable Regulation	304b	307a	311	Priority Poll.	111	112b	112r	110	313	302a	8d HSDR	MTL	8a PAIR	P	U
Acetic acid			X		X										
Copper ion	X	X		X				X	X						
Copper sulfate pentahydrate	X	X		X				X	X						
Ethylene glycol					X	X			X			X			
Hydrogen peroxide										X					
Hydrochloric acid			X			X	X		X	X		X			
Phosphoric acid			X												
Sodium hydroxide			X												
Sulfuric acid			X		X										
CBI Chemicals (9)									1		1		1		

Note: For technologies with more than one process submitted for evaluation (i.e., nickel/gold, OSP, immersion tin), the number of listed chemicals subject to regulation reflects the total number of chemicals for both processed.

Abbreviations and definitions:
CAA - Clean Air Act
CAA 111 - Standards of Performance for New Stationary Sources of
Air Pollutants-Equipment Leaks Chemical List
CAA 112b - Hazardous Air Pollutant
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CWA - Clean Water Act
CWA 304b - Effluent Limitations Guidelines
CWA 307a - Toxic Pollutants
CWA 311 - Hazardous Substances
CWA Priority Pollutants
EPCRA - Emergency Planning and Community Right-to-Know Act
EPCRA 302a - Extremely Hazardous Substances
EPCRA 313 - Toxic Chemical Release Inventory

RCRA - Resource Conservation and Recovery Act
RCRA P Waste - Listed acutely hazardous waste
RCRA U Waste - Listed hazardous waste
SARA - Superfund Amendments and Reauthorization Act
SARA 110 - Superfund Site Priority Contaminant
TSCA - Toxic Substances Control Act
TSCA 8d HSDR - Health & safety data reporting rules
TSCA MTL - Master Testing List
TSCA 8a PAIR - Preliminary Assessment Information Rule

Table 4-61. Summary of Regulations that May Apply to Chemicals Used in Immersion Silver Technology

Process Chemical	Chemicals Subject to Applicable Regulation														
	CWA				CAA			SARA	EPCRA		TSCA			RCRA Waste	
	304b	307a	311	Priority Poll.	111	112b	112r	110	313	302a	8d HSDR	MTL	8a PAIR	P	U
Hydrogen peroxide										X		X			
Phosphoric acid		X							X						
Silver nitrate	X	X	X	X				X					X		
Sodium hydroxide		X							X						
Sulfuric acid		X			X				X						
CBI chemicals (5)			1			1			1	1					

Note: For technologies with more than one process submitted for evaluation (i.e., nickel/gold, OSP, immersion tin), the number of listed chemicals subject to regulation reflects the total number of chemicals for both processed.

Abbreviations and definitions:
CAA - Clean Air Act
CAA 111 - Standards of Performance for New Stationary Sources of
Air Pollutants-Equipment Leaks Chemical List
CAA 112b - Hazardous Air Pollutant
CAA 112r - Risk Management Program
CWA - Clean Water Act
CWA 304b - Effluent Limitations Guidelines
CWA 307a - Toxic Pollutants
CWA 311 - Hazardous Substances
CWA Priority Pollutants
EPCRA - Emergency Planning and Community Right-to-Know Act
EPCRA 302a - Extremely Hazardous Substances
EPCRA 313 - Toxic Chemical Release Inventory

RCRA - Resource Conservation and Recovery Act
RCRA P Waste - Listed acutely hazardous waste
RCRA U Waste - Listed hazardous waste
SARA - Superfund Amendments and Reauthorization Act
SARA 110 - Superfund Site Priority Contaminant
TSCA - Toxic Substances Control Act
TSCA 8d HSDR - Health & safety data reporting rules
TSCA MTL - Master Testing List
TSCA 8a PAIR - Preliminary Assessment Information Rule

Table 4-62. Summary of Regulations that May Apply to Chemicals Used in Immersion Tin Technology

Chemicals Subject to Applicable Regulation														
Process Chemical	**CWA**				**CAA**			**SARA**	**EPCRA**		**TSCA**			**RCRA Waste**	
	304b	307a	311	Priority Poll.	111	112b	112r	110	313	302a	8d HSDR	MTL	8a PAIR	P	U
Hydrochloric acid			X			X	X		X	X		X			
Phosphoric acid			X						X						
Silver nitrate	X	X	X	X				X	X				X		
Sulfuric acid			X		X					X					
Thiourea									X						U219
Urea															
CBI Chemicals (16)			2		2	1			3		2	3	2		1

Note: For technologies with more than one process submitted for evaluation (i.e., nickel/gold, OSP, immersion tin), the number of listed chemicals subject to regulation reflects the total number of chemicals for both processed.

Abbreviations and definitions:
CAA - Clean Air Act
CAA 111 - Standards of Performance for New Stationary Sources of
Air Pollutants-Equipment Leaks Chemical List
CAA 112b - Hazardous Air Pollutant
CAA 112r - Risk Management Program
CWA - Clean Water Act
CWA 304b - Effluent Limitations Guidelines
CWA 307a - Toxic Pollutants
CWA 311 - Hazardous Substances
CWA Priority Pollutants
EPCRA - Emergency Planning and Community Right-to-Know Act
EPCRA 302a - Extremely Hazardous Substances
EPCRA 313 - Toxic Chemical Release Inventory

RCRA - Resource Conservation and Recovery Act
RCRA P Waste - Listed acutely hazardous waste
RCRA U Waste - Listed hazardous waste
SARA - Superfund Amendments and Reauthorization Act
SARA 110 - Superfund Site Priority Contaminant
TSCA - Toxic Substances Control Act
TSCA 8d HSDR - Health & safety data reporting rules
TSCA MTL - Master Testing List
TSCA 8a PAIR - Preliminary Assessment Information Rule

REFERENCES

Badgett, Lona, Beth Hawke and Karen Humphrey. 1995. *Analysis of Pollution Prevention and Waste Minimization Opportunities Using Total Cost Assessment: A Study in the Electronic Industry*. Seattle, WA. Pacific Northwest Pollution Prevention Research Center Publication.

Ferguson, John H. 1996. *Mean Square Foot Costs: Means-Southern Construction Information Network*. Kingston, MA: R.S. Means, Co., Inc. Construction. Publishers and Consultants.

Fisher, Helen S. 1999. *American Wages and Salary Survey*, 3rd Ed. Detroit, MI: Gale Research Inc. (An International Thompson Publishing Co.)

Iman, R.L. et al. 1995. "Evaluation of Low-Residue Soldering for Military and Commercial Applications: A Report from the Low-Residue Soldering Task Force." June.

Iman, R.L., J.F. Koon, et al. 1997. "Screening Test Results for Developing Guidelines for Conformal Coating Usage and for Evaluating Alternative Surface Finishes." CCAMTF Report. June.

Iman, R.L., J. Fry, R. Ragan, J.F. Koon and J. Bradford. 1998. "A Gauge Repeatability and Reproducibility Study for the CCAMTF Automated Test Set." CCAMTF Report. March.

Joint Group on Acquisition Pollution Prevention (JG-APP) Joint Test Protocol CC-P-1-1 for Validation of alternatives to Lead-Containing Surface Finishes, for Development of Guidelines for Conformal Coating Usage, and for Qualification of Low-VOC Conformal Coatings. 1998.

Iman, R.L. 1994. A Data-Based Approach to Statistics. Duxbury Press.

The Institute for Interconnecting and Packaging Electronic Circuits. 1995. "Ionic Analysis of Circuit Boards Ion Chromatography Method." IPC-TM-650 Test Methods Manual. Lincolnwood, IL: IPC.

Vishanoff, Richard. 1995. *Marshall Valuation Service: Marshall and Swift the Building Cost People*. Los Angeles, CA: Marshall and Swift Publications.

White, Allan L., Monica Becker and James Goldstein. 1992. *Total Cost Assessment. Accelerating Industrial Pollution Prevention Through Innovative Project Financial Analysis: With Application to Pulp and Paper Industry.* U.S. EPA's Office of Pollution Prevention and Toxics, Washington, DC.

U.S. EPA (Environmental Protection Agency). 1998. *Pollution Prevention and Control Survey*.